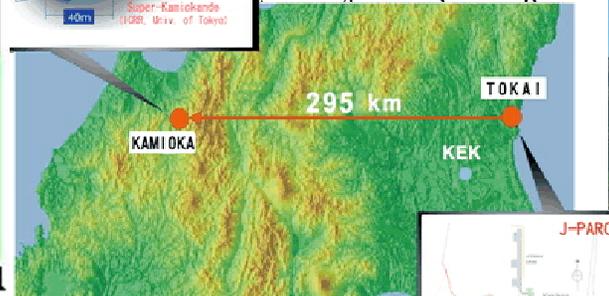
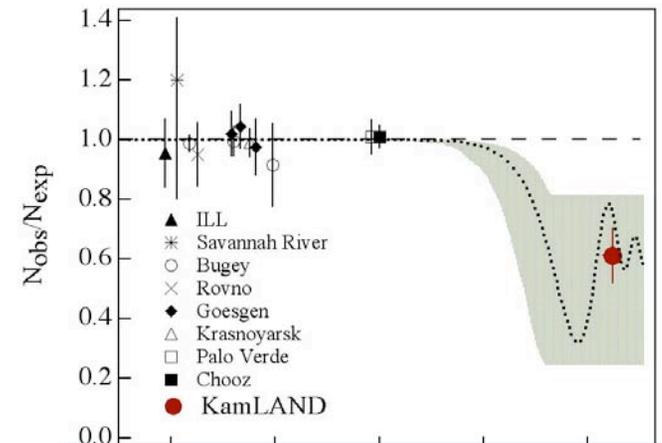
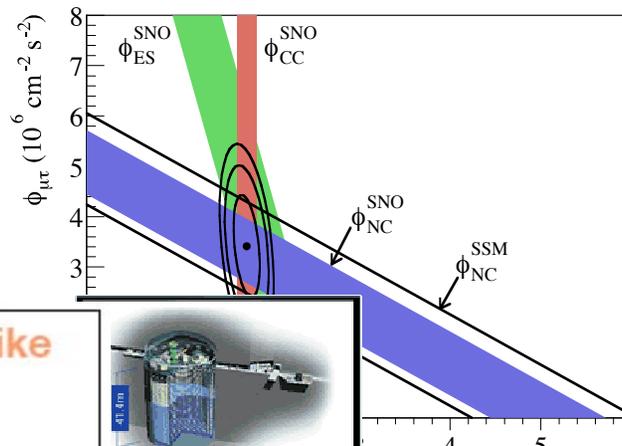
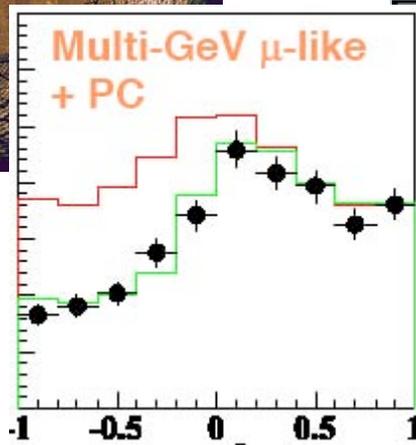
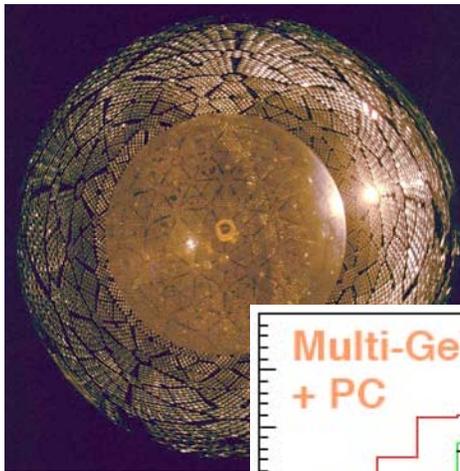


Recent Discoveries in Neutrino Physics

& Prospects for the Future

Karsten M. Heeger

Lawrence Berkeley National Laboratory



$\bar{\nu}_\mu$

γ_{CMB}

$\nu_{\text{Sterile?}}$

γ_{CMB}

Dark Energy?

$\bar{\nu}_\tau$



Dark Matter?

$\bar{\nu}_e$

$\bar{\nu}_{\text{Sterile?}}$

γ_{CMB}

Neutrino Density in the Universe

0.5 proton per cm^3

~ 330 neutrinos per cm^3

Big-Bang neutrinos are approximately as numerous as the Big-Bang photons.

Neutrinos from the Big Bang



High Energy Cosmic Neutrinos



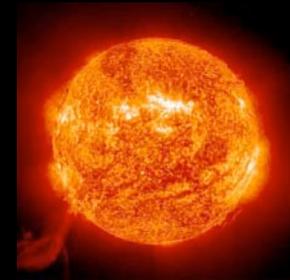
*Atmospheric
Neutrinos*

Supernova Neutrinos

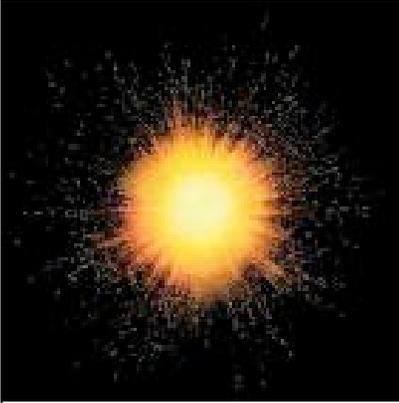
Geo Neutrinos

*Accelerator&Reactor
Neutrinos*

Solar Neutrinos



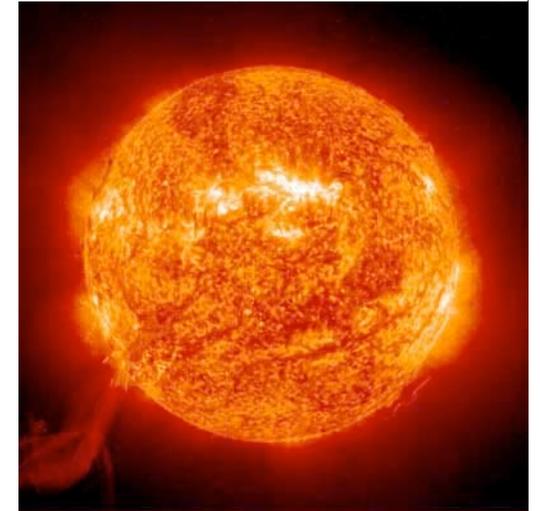
Neutrino Energies



Big-Bang neutrinos ~ 0.0004 eV

Neutrinos from the Sun < 20 MeV
depending of their origin.

Atmospheric neutrinos \sim GeV



Antineutrinos from nuclear
reactors < 10.0 MeV

Neutrinos from accelerators up to GeV (10^9 eV)



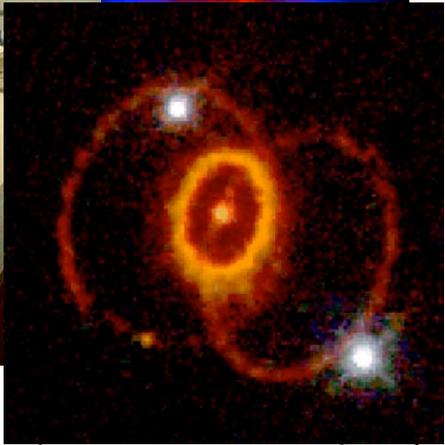
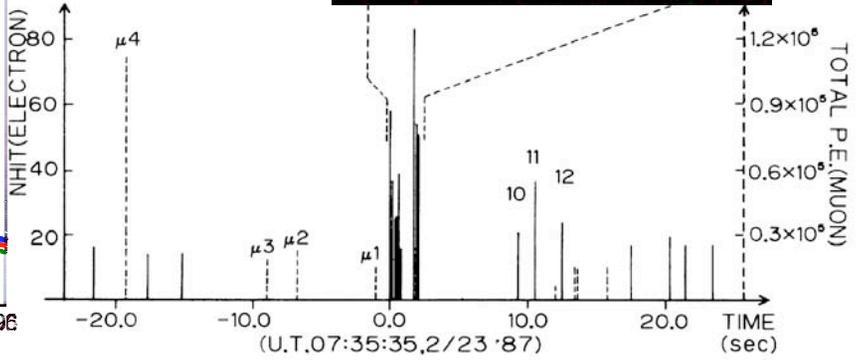
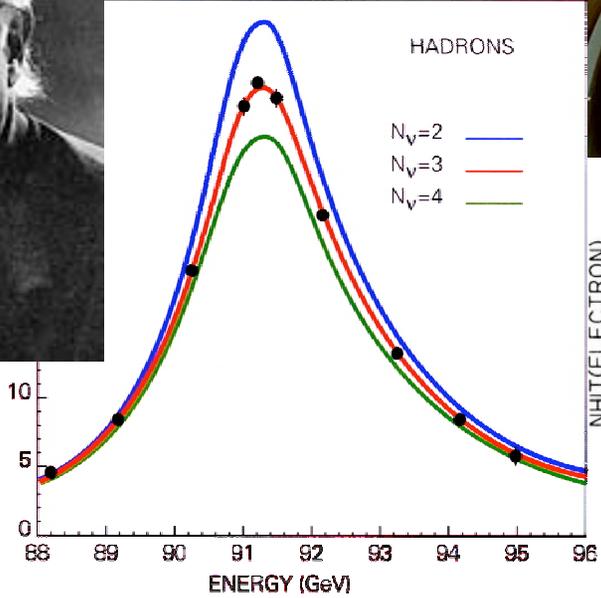
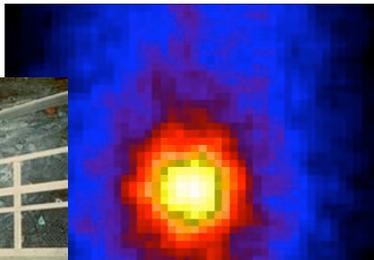
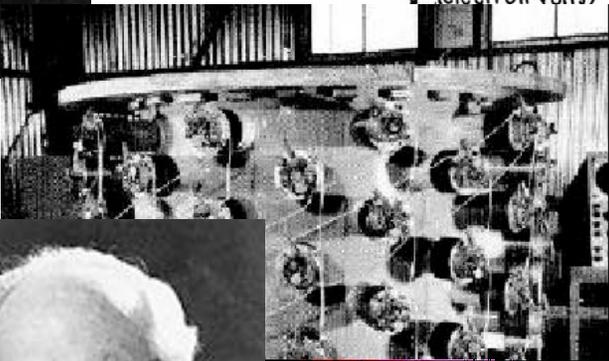
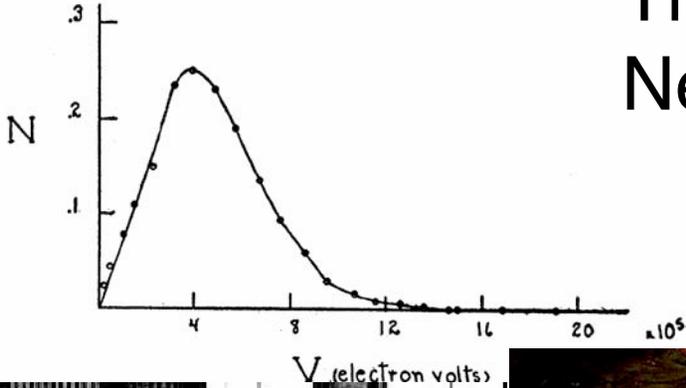
Matter in the Universe



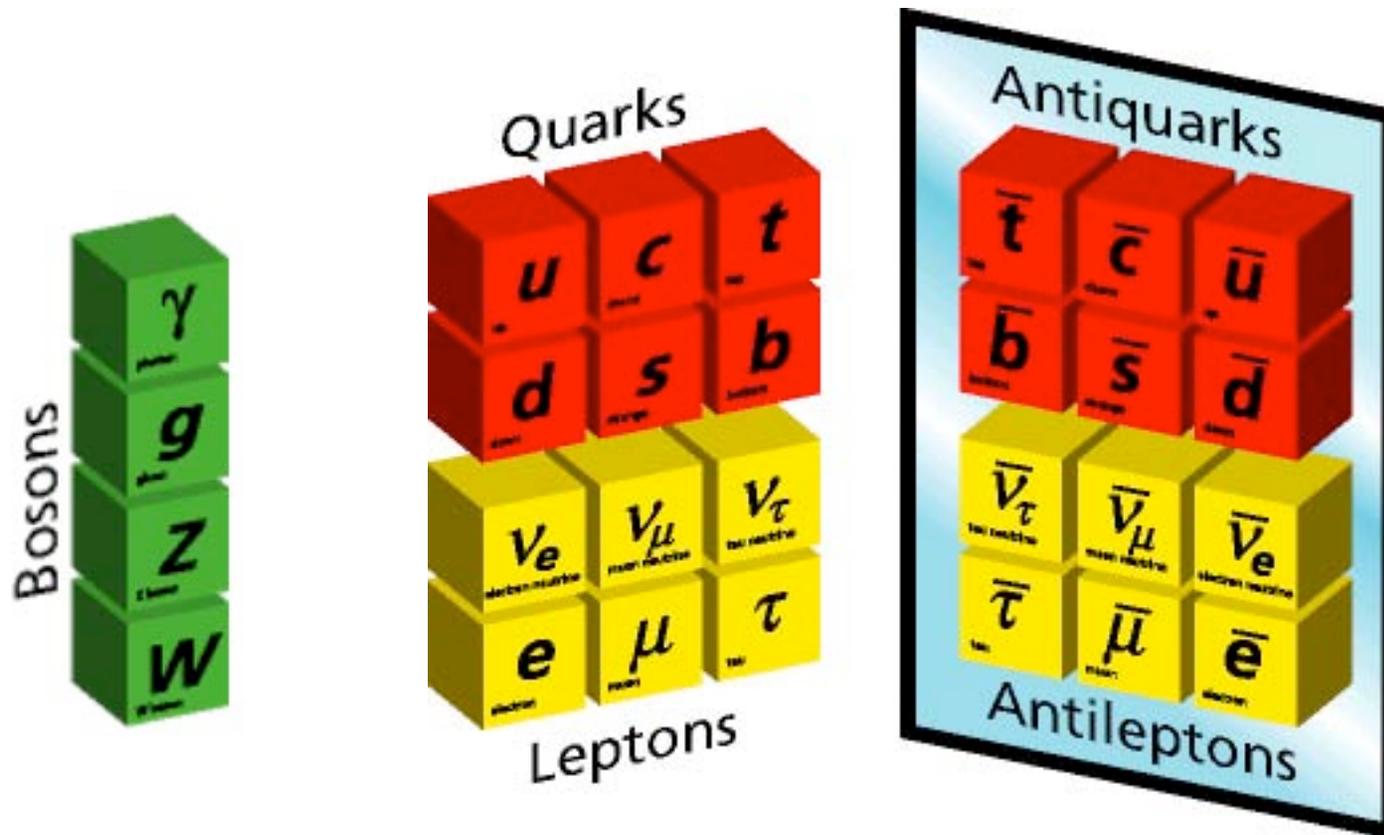
*What is dark matter?
What is dark energy?
Why is there no antimatter?*

Leptogenesis from CP violation with massive neutrinos may explain matter-antimatter asymmetry in Universe

The First 60 Years of Neutrino Physics



Elementary Particles



Neutrino Cross Section is Very Small

Weak interactions are weak because of the massive W and Z boson exchange

$$\sigma^{\text{weak}} \propto G_F^2 \propto (1/M_{W \text{ or } Z})^4$$

$$M_W \sim 80 \text{ GeV}$$

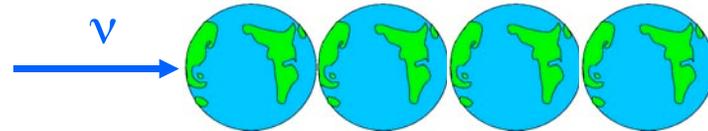
$$M_Z \sim 91 \text{ GeV}$$

For 100 GeV neutrinos:

$$\sigma(\nu e) \sim 10^{-40} \quad \sigma(\nu p) \sim 10^{-36} \text{ cm}^2$$

$$\sigma(pp) \sim 10^{-26} \text{ cm}^2$$

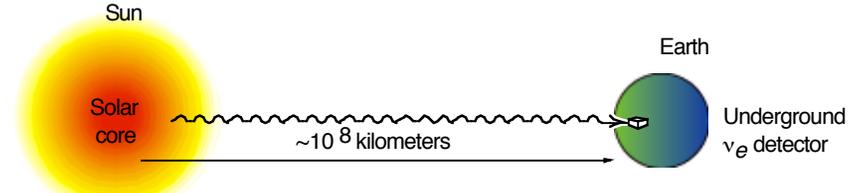
A neutrino has a good chance of traveling through 200 Earths before interacting at all!



Mean free path length in steel $\sim 3 \times 10^9 \text{ m}$

→ Need big detectors and lots of ν's

Experimental Studies



Natural Sources

The Sun

³⁷Cl
GALLEX
SAGE

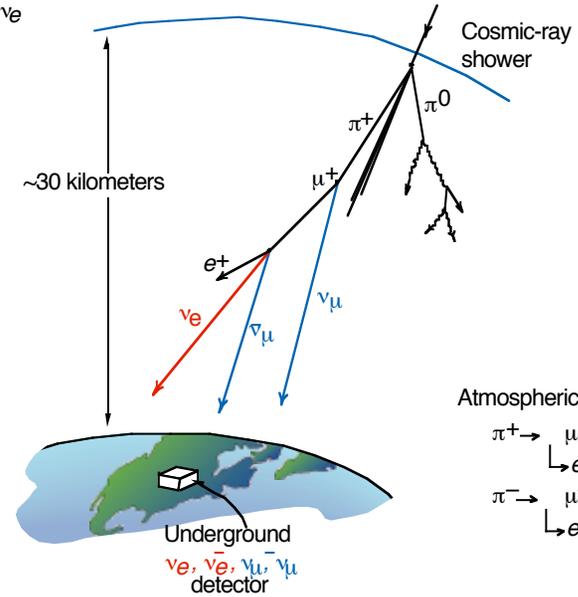
Kamiokande
SuperKamiokande
SNO ★

Atmospheric Neutrinos

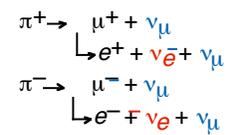
IMB
Soudan
MACRO

Kamiokande ★
SuperKamiokande
...

Primary neutrino source
 $p + p \rightarrow D + e^+ + \nu_e$



Atmospheric neutrino source



Man-Made Sources

Accelerators

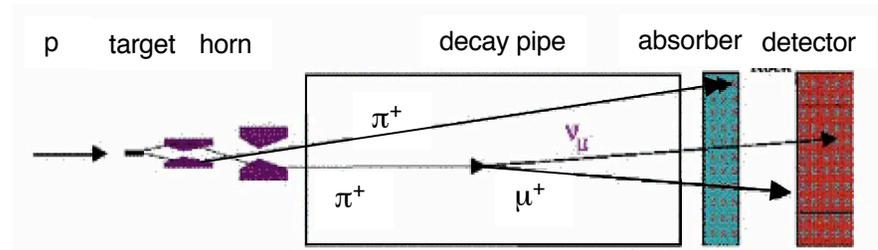
K2K ★
Opera
...

Chorus
(LSND)

Nuclear Reactors

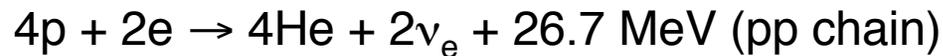
Bugey
ILL
Palo Verde

Goesen
Chooz
KamLAND ★



Birth of Neutrino Astrophysics

Solar Neutrino Flux Measurements

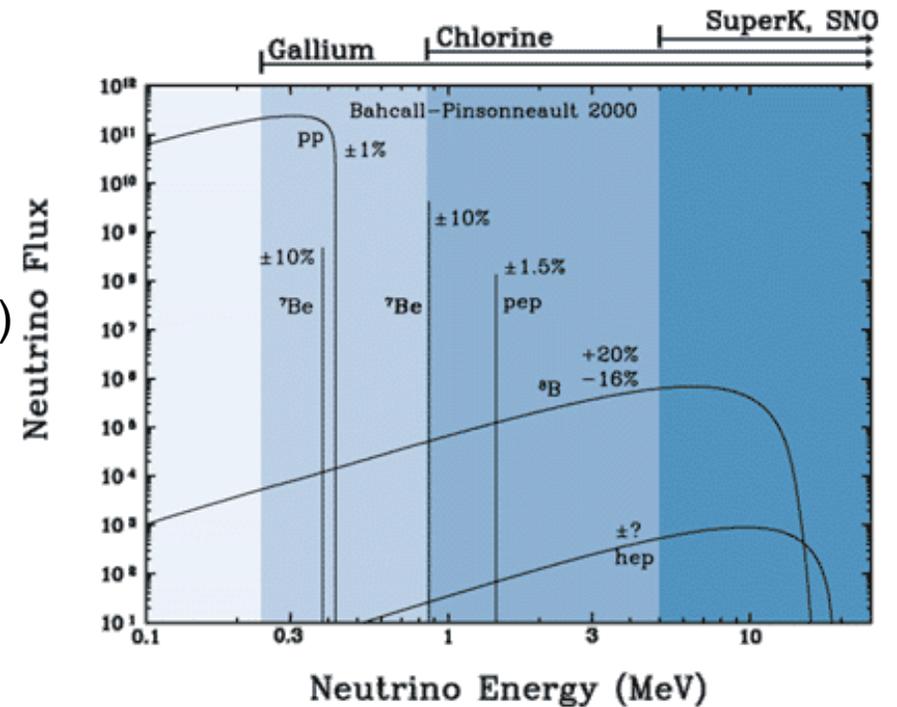


1960's

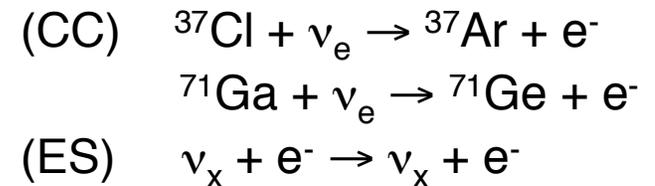
- Ray Davis' Chlorine detector
- First Solar Model calculations

For 30 years

CC and ES measurements of solar ν_e



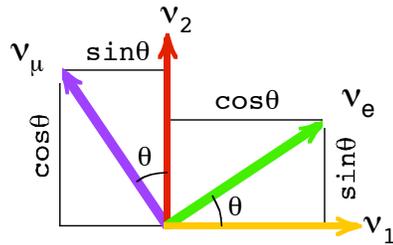
Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$



→ Data are incompatible with standard and non-standard solar models

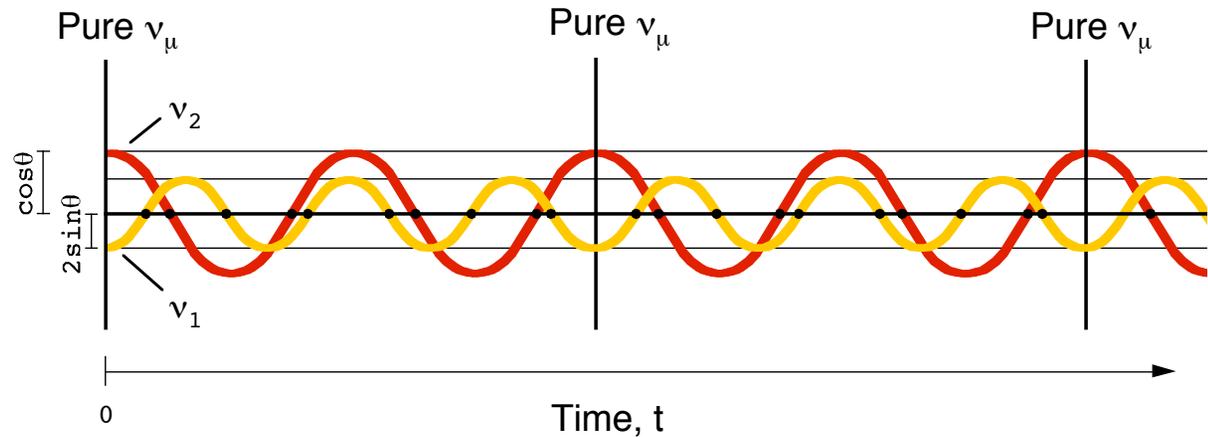
Neutrino Oscillation

Neutrino States



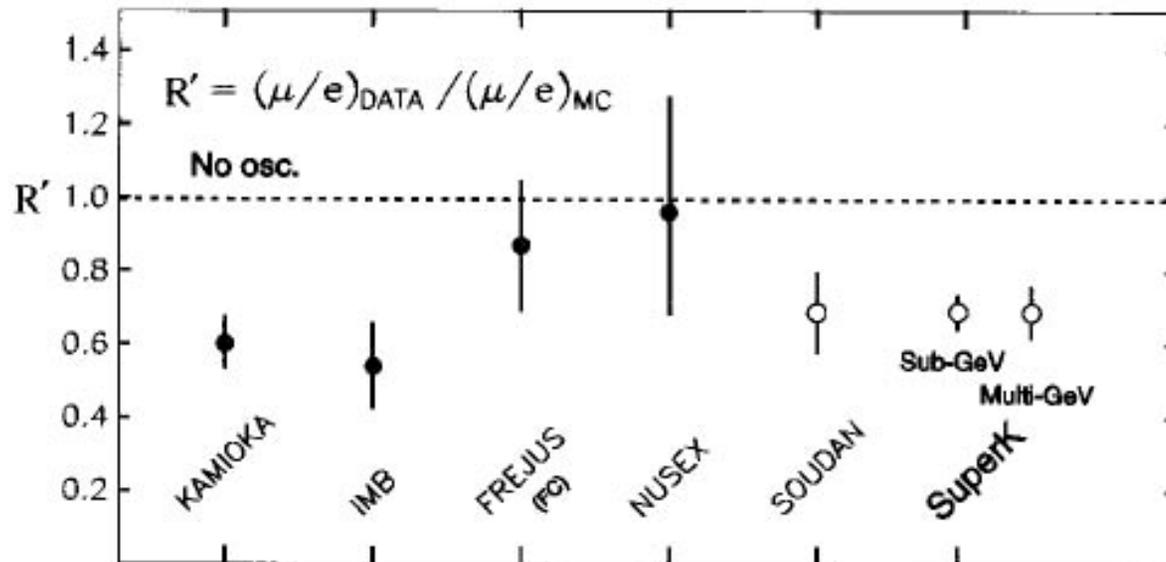
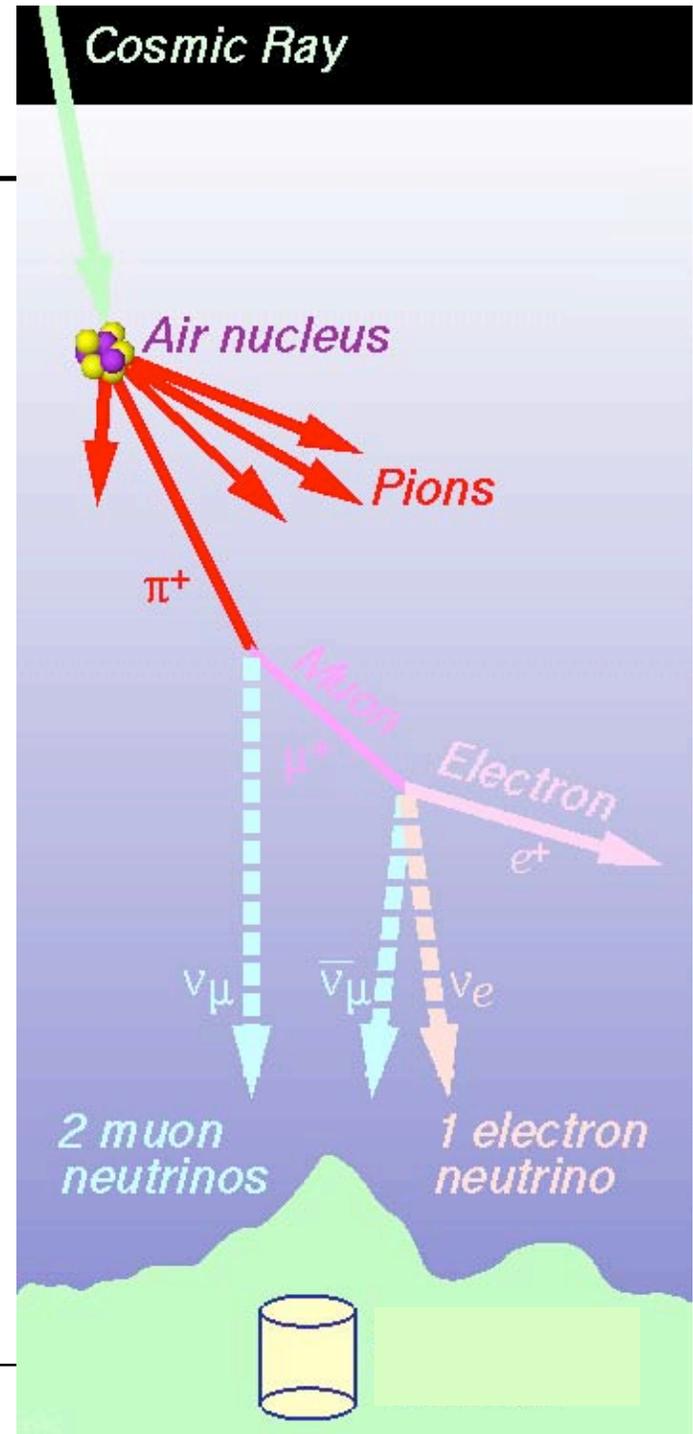
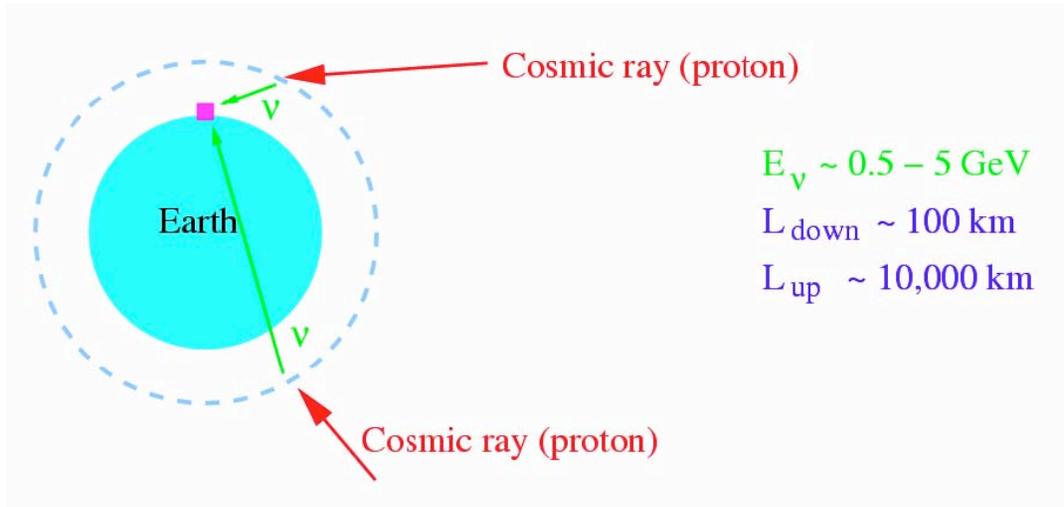
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ 2\sin\theta & \cos\theta \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Time Evolution



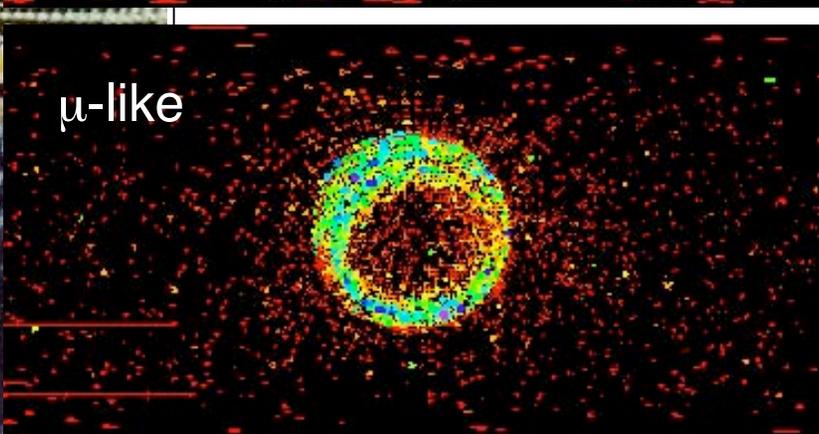
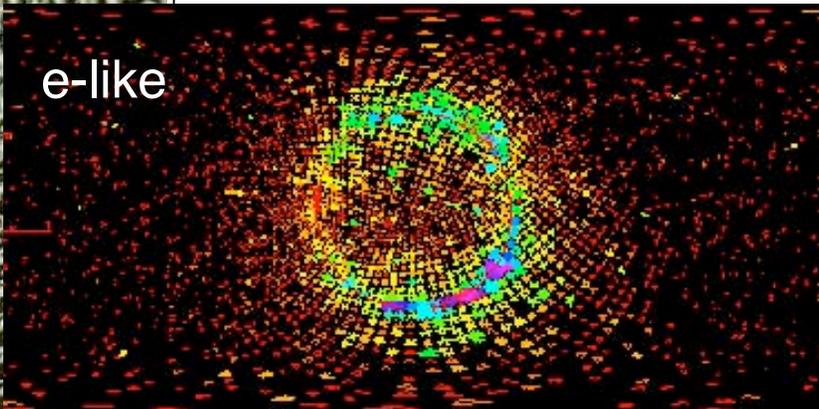
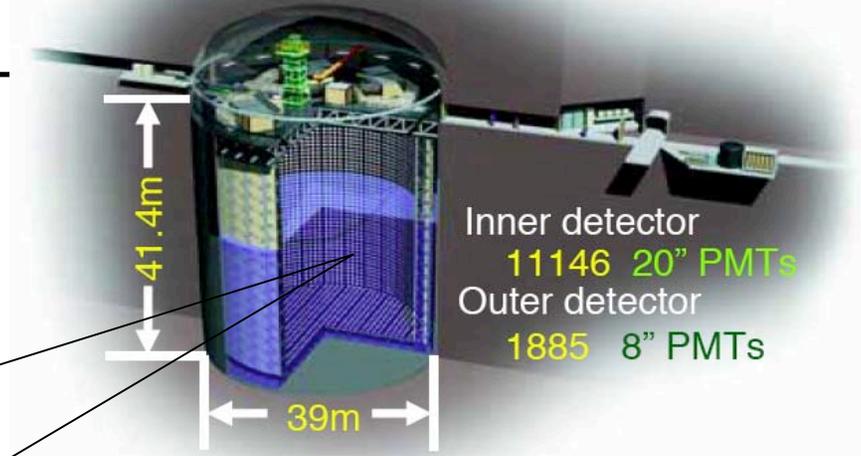
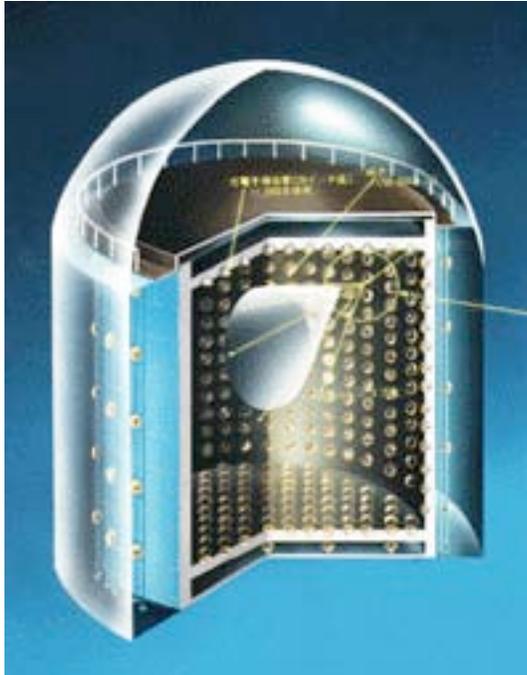
$$P_{i \rightarrow i} = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E} \right)$$

Atmospheric Neutrino Studies



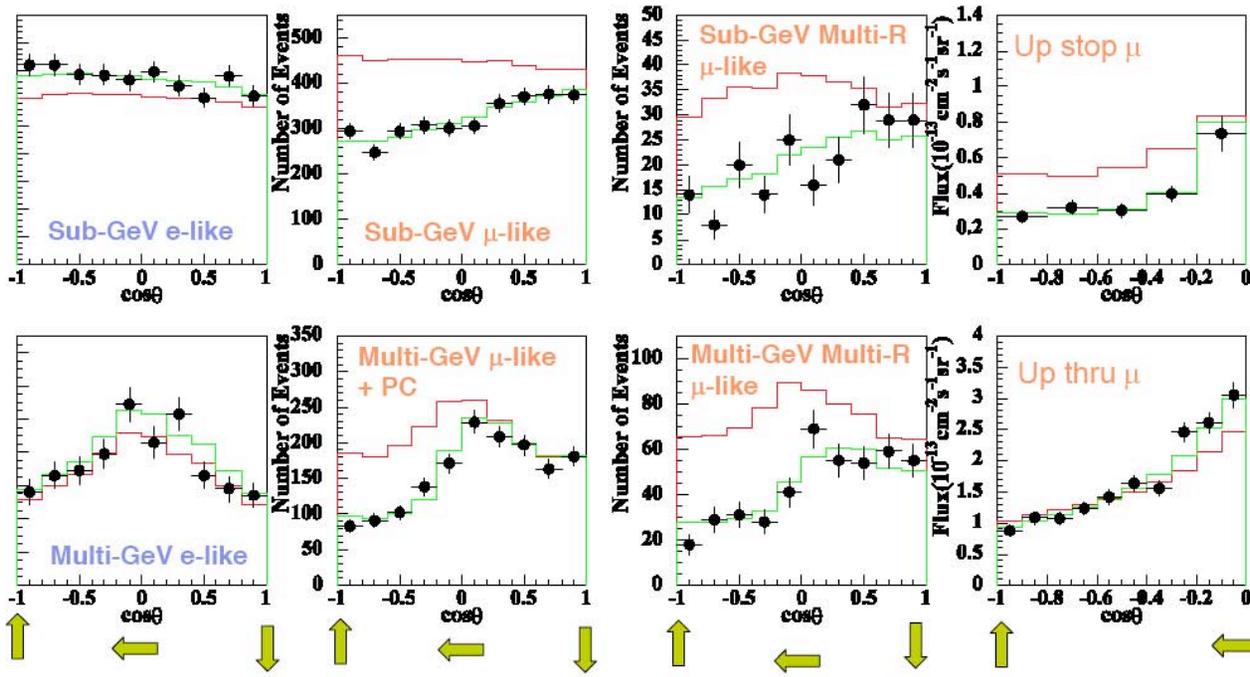
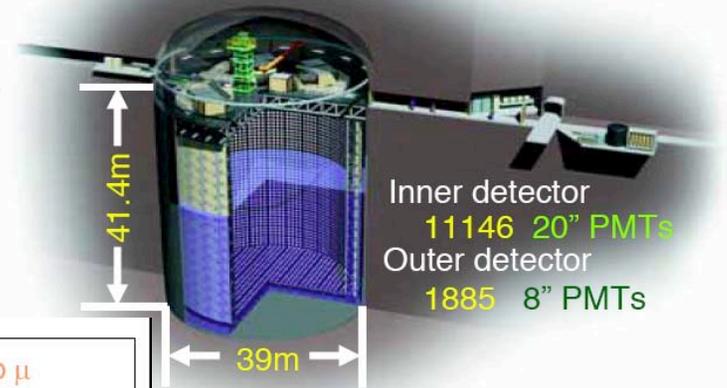
Super-Kamiokande

Atmospheric Neutrino Studies

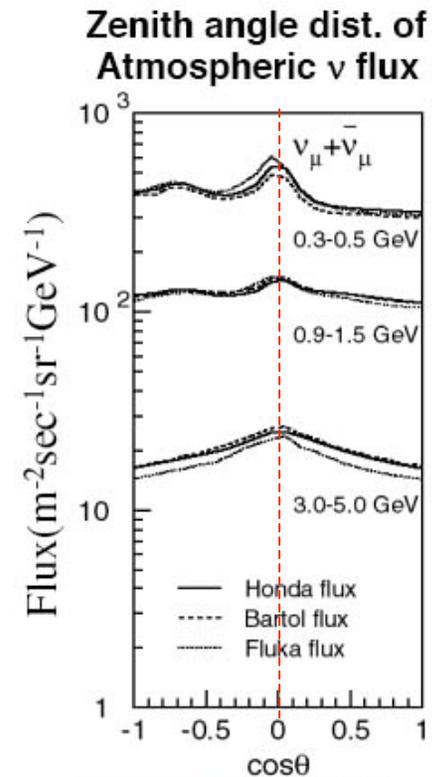


Super-Kamiokande

Atmospheric Neutrino Studies



— Best fit $\nu_\mu \rightarrow \nu_\tau$ 2-flavor osc.
 $\sin^2 2\theta = 1.0, \Delta m^2 = 2.0 \times 10^{-3} \text{ eV}^2$
— Null oscillation

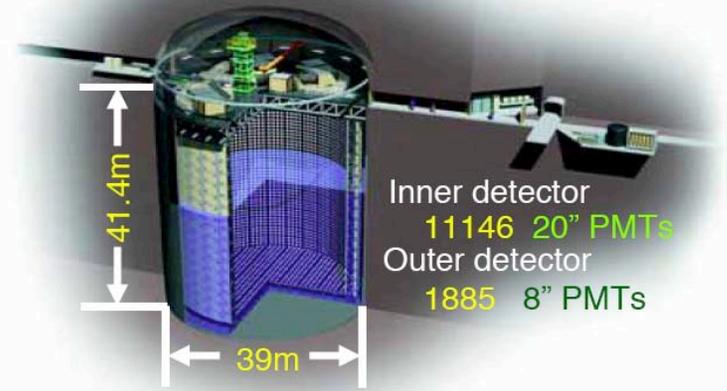


$E_\nu > \text{a few GeV}$
Up/Down Symmetry

KEK to Kamioka (K2K) Experiment

Accelerator-based long baseline neutrino oscillation experiment to test atmospheric oscillations

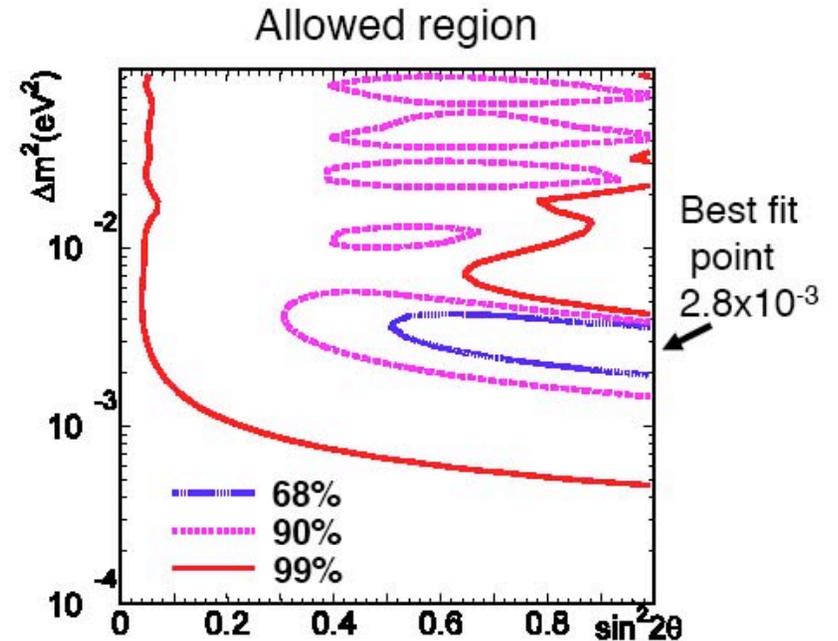
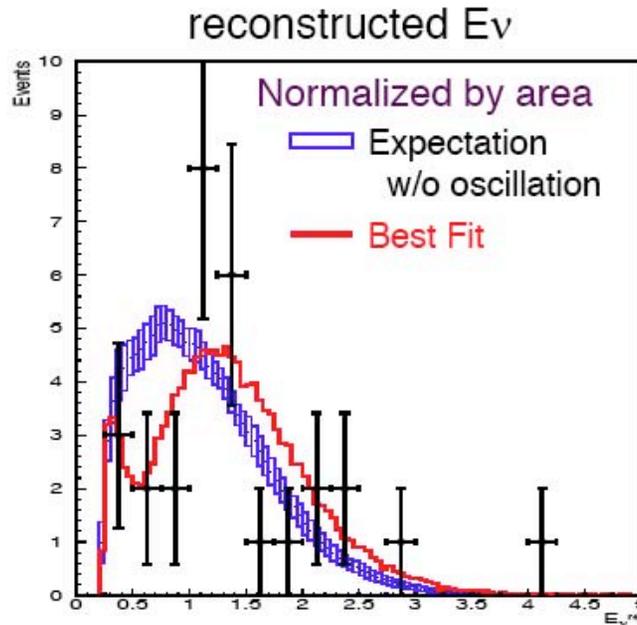
	atm	K2K
L	10-10 ⁴ km	250 km
E _ν	0.1~100 GeV	~ 1.3 GeV
Δm ²	10 ⁻¹ ~10 ⁻⁴ eV ²	> 2x10 ⁻³ eV ²
ν _e /ν _μ	50%	~1%



data from 1999-2001

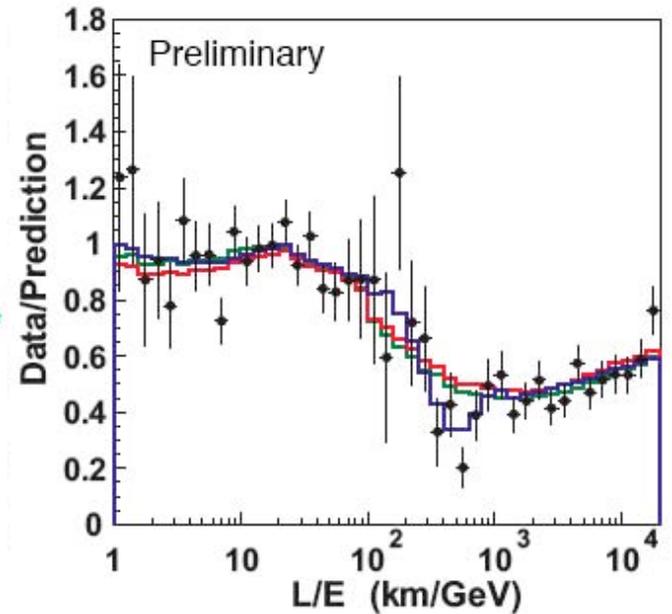
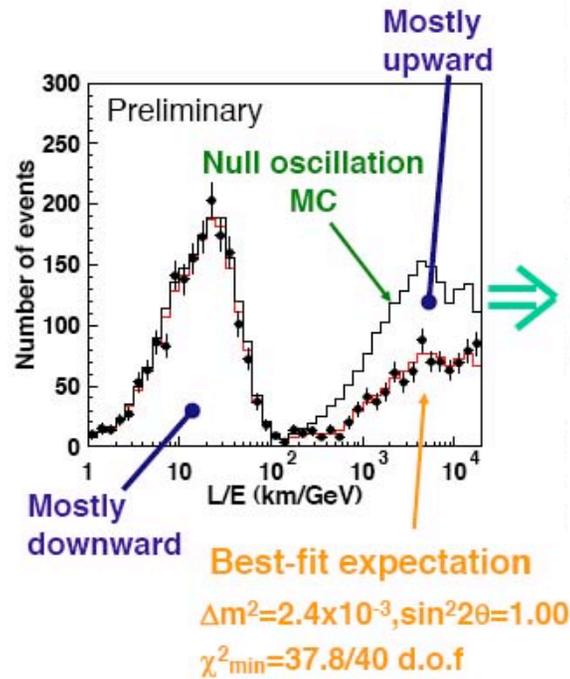
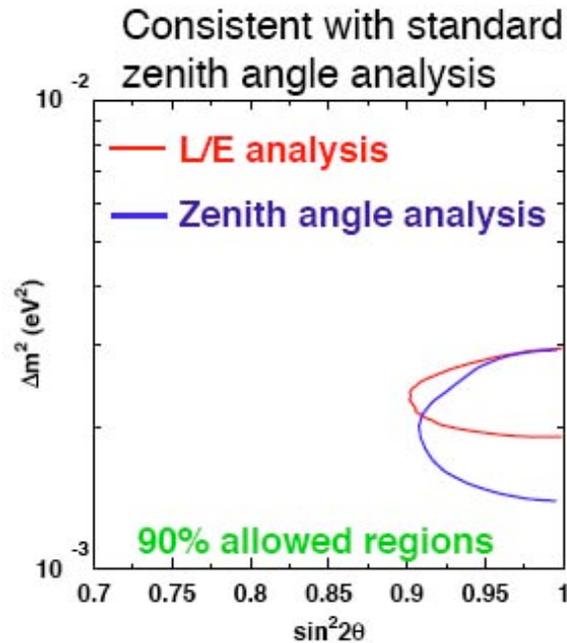
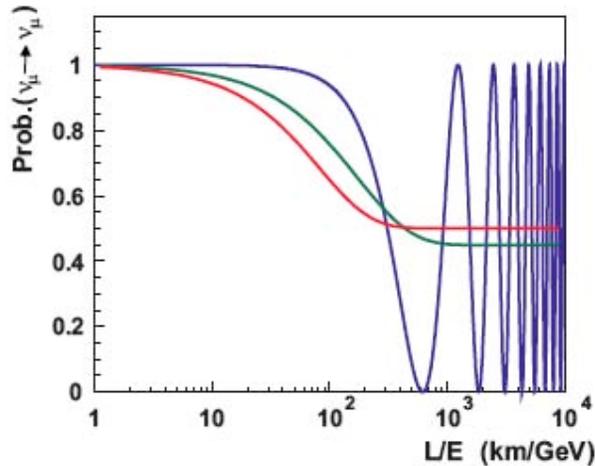
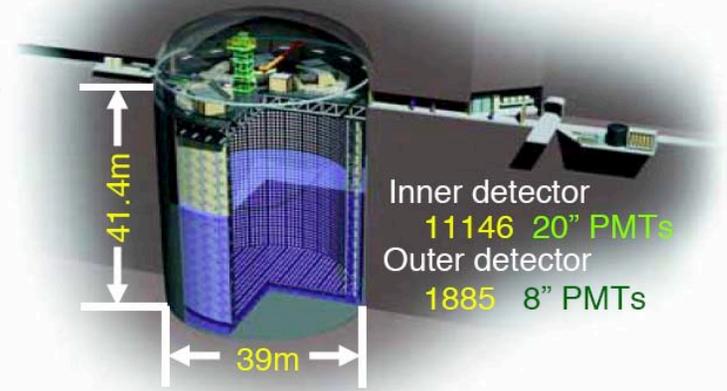
expected: 80.1 events

observed: 56 events



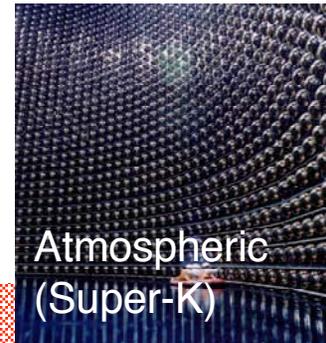
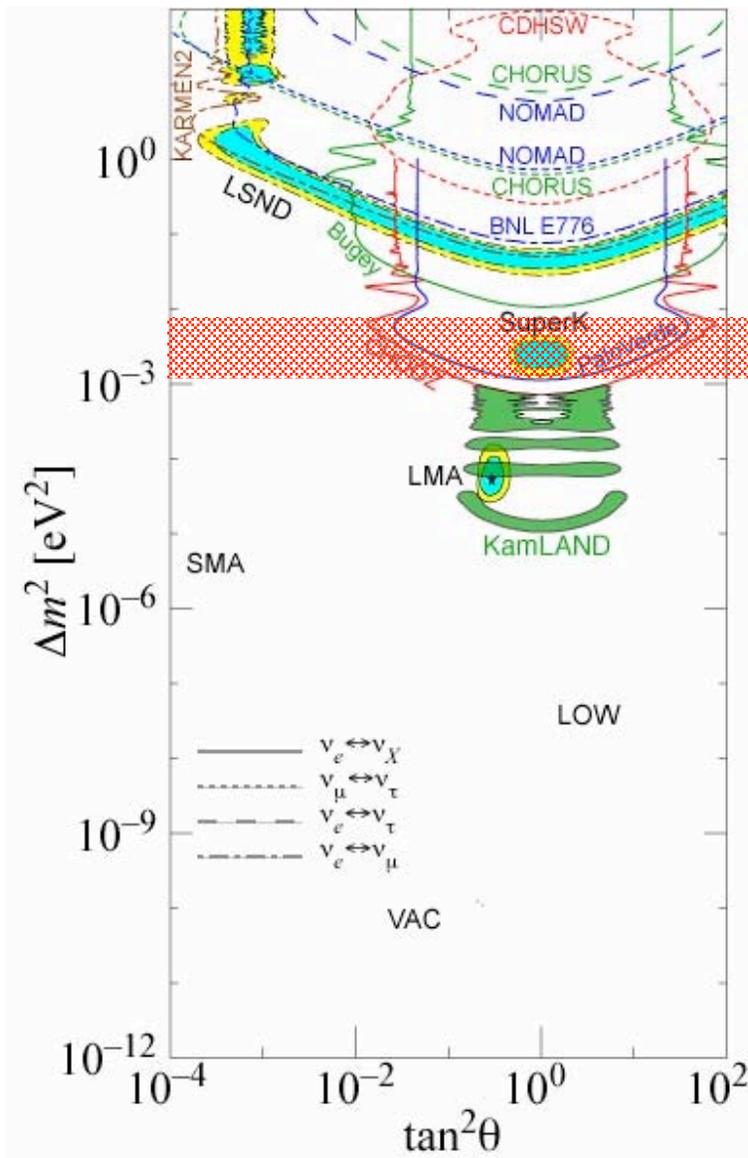
Super-Kamiokande L/E Analysis

Searching for Direct Evidence of Oscillations

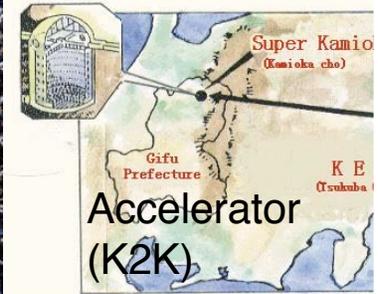


First dip is observed as expected from neutrino oscillation

Atmospheric Neutrino Oscillations



Atmospheric
(Super-K)



Accelerator
(K2K)

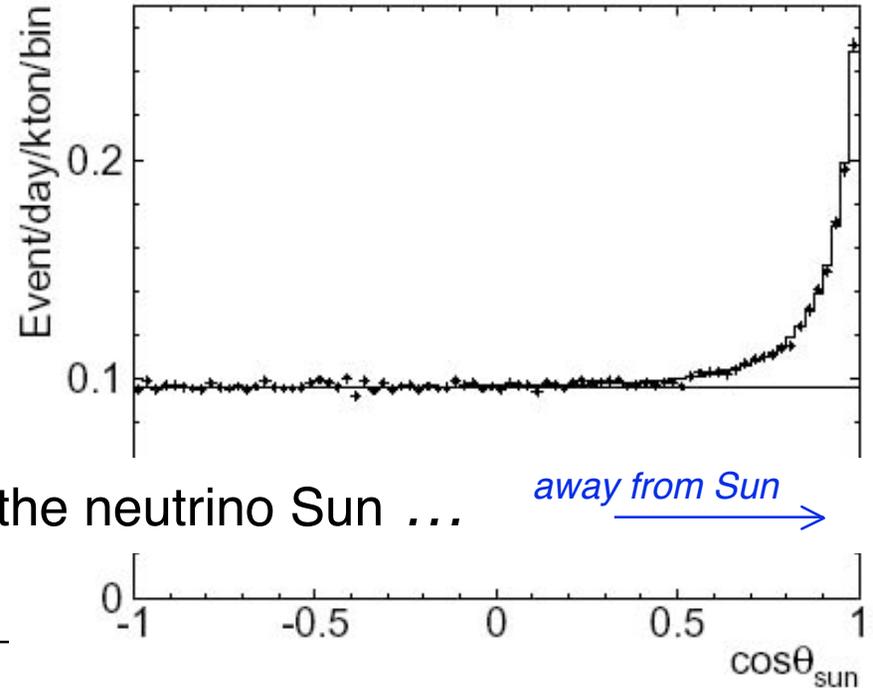
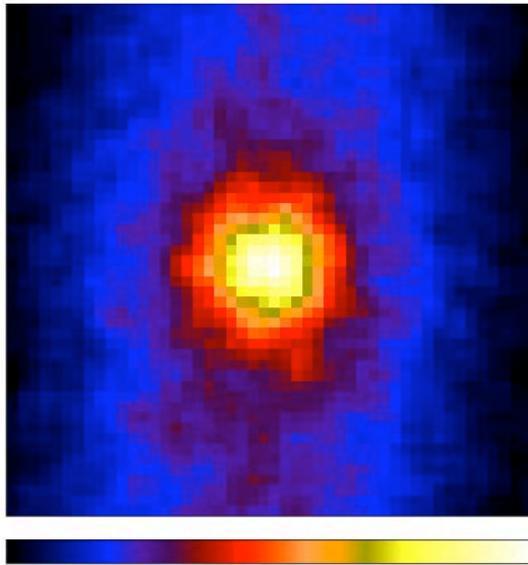
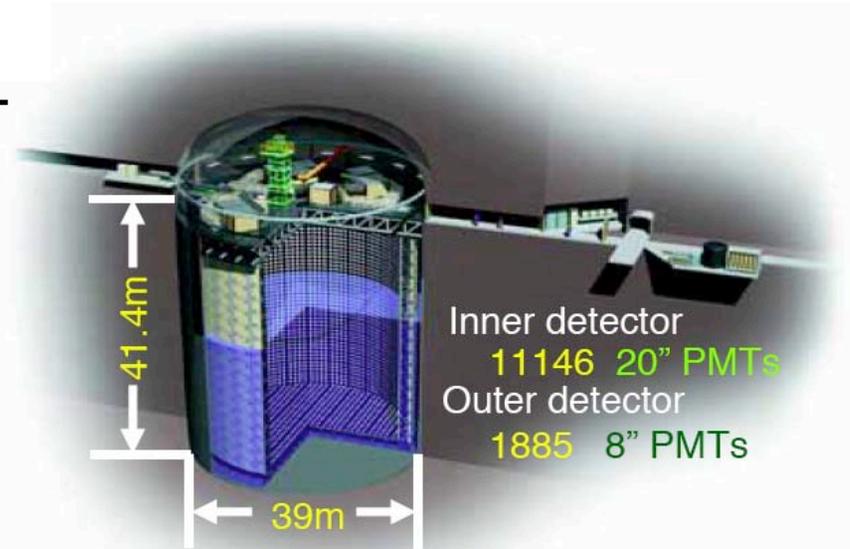
Atmospheric ν data explained extremely well by oscillations

- primarily $\nu_{\mu} \rightarrow \nu_{\tau}$ conversion
- mixing angle θ_{23} is near maximal
- $\Delta m^2 \sim 2 \times 10^{-3} \text{ eV}^2$

High-Statistics Solar Neutrino Observations at Super-Kamiokande

Elastic Scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$

Data/SSM = 0.451 ± 0.005 + 0.016
 (stat) - 0.014 (sys.)



Observing the neutrino Sun ...

away from Sun →

Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.)



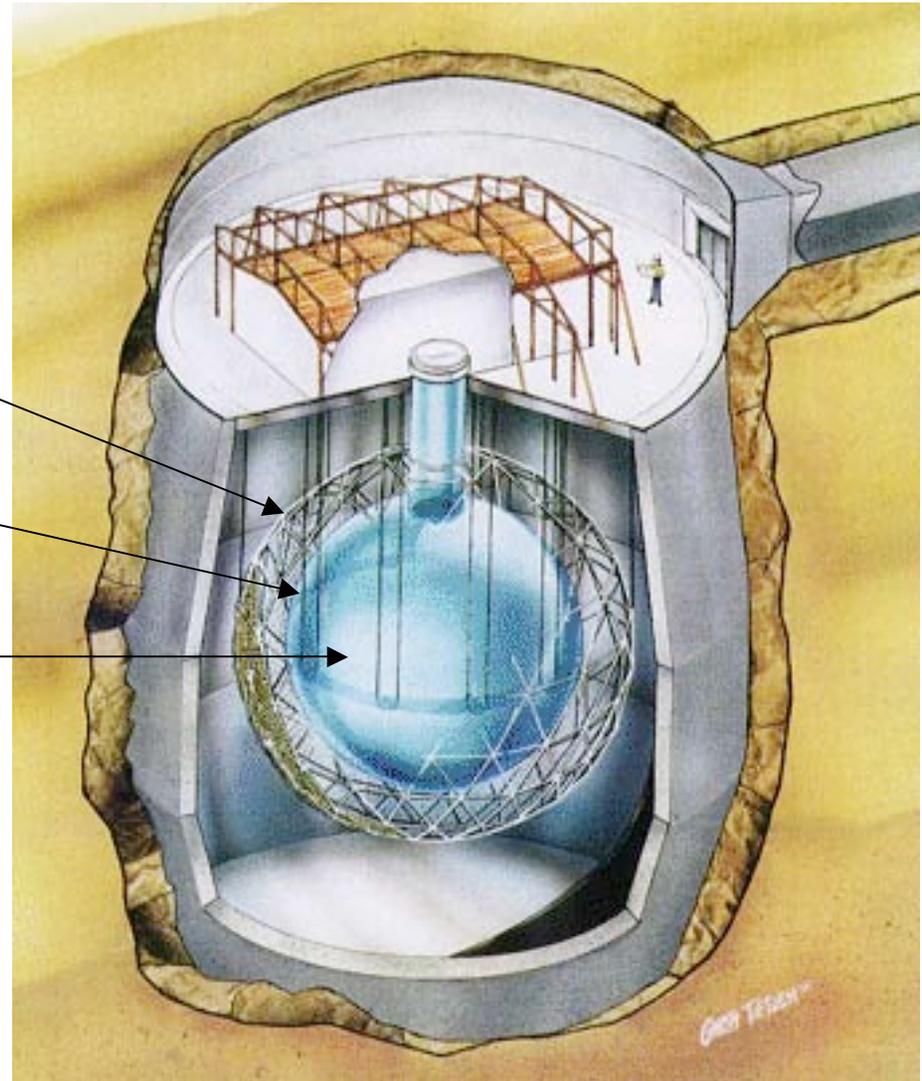
PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

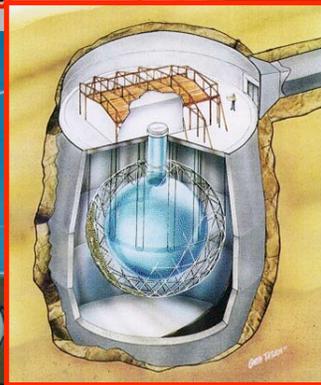
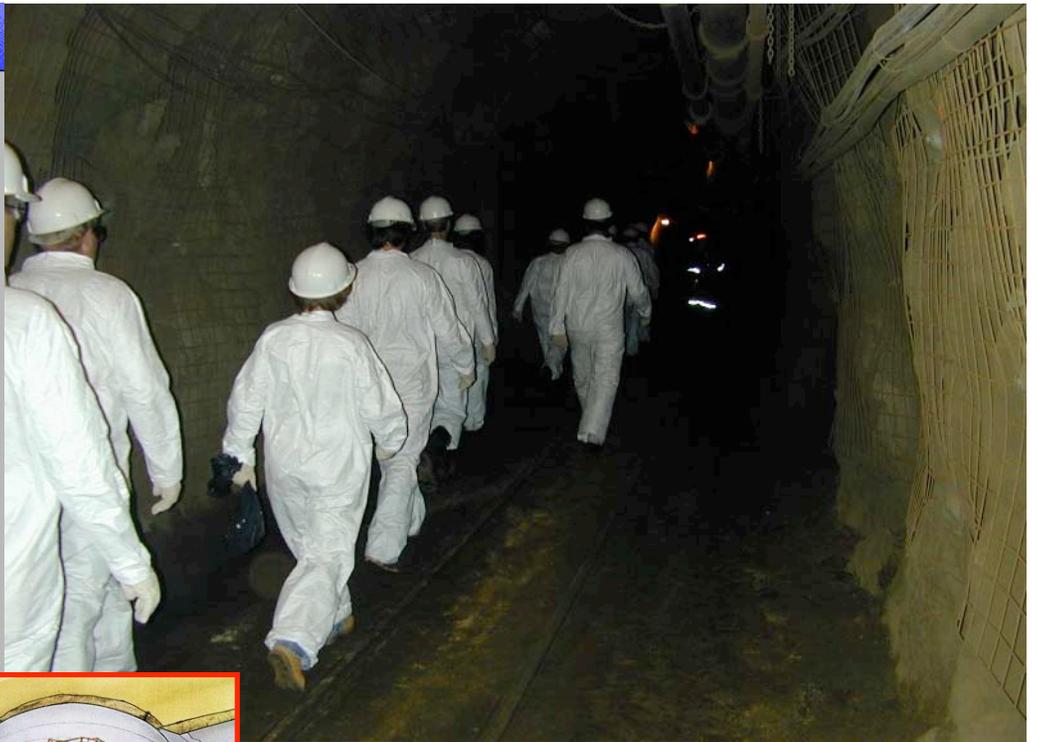
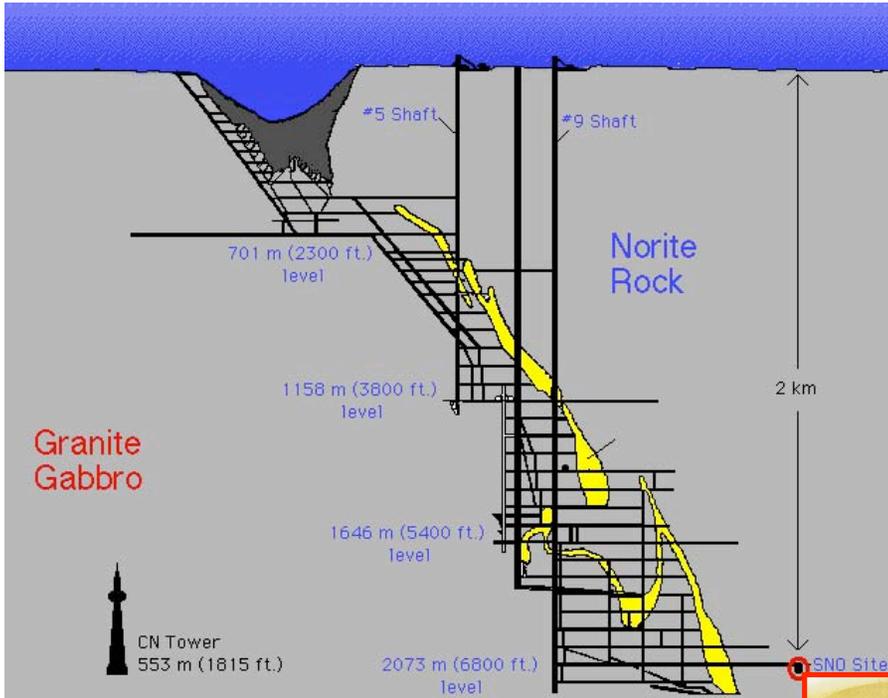
Acrylic Vessel, 12 m diameter

1000 Tonnes D_2O

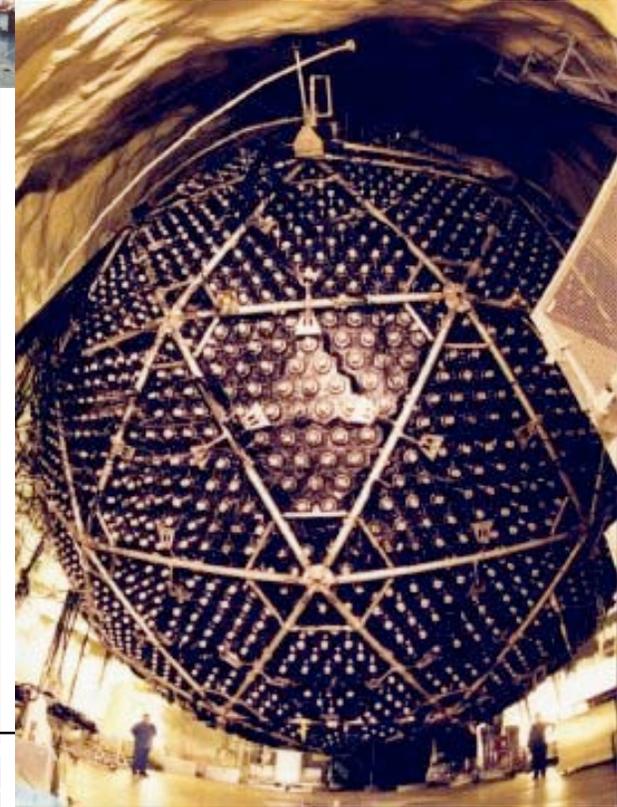
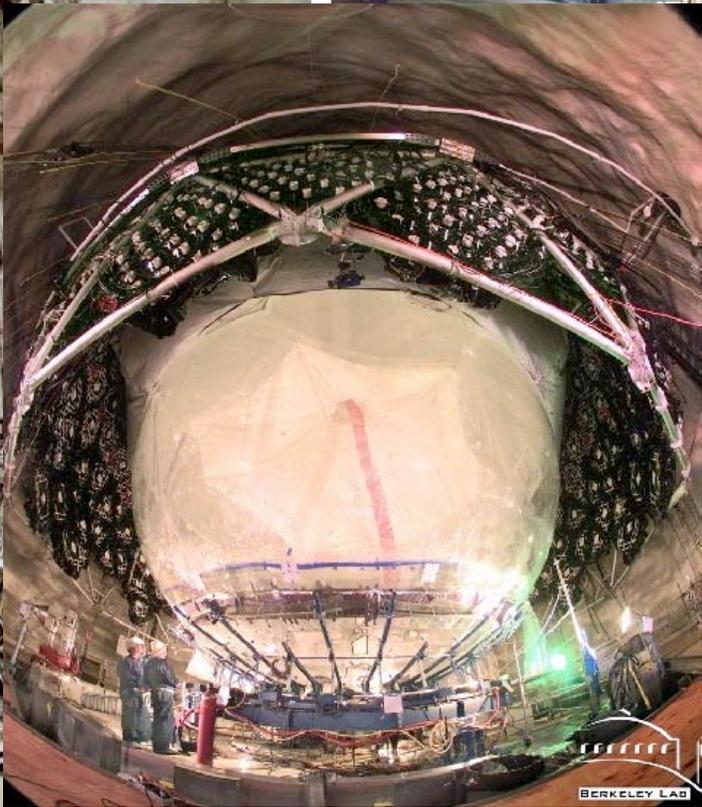
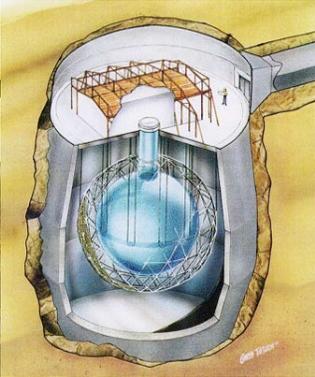
Need solar model-independent measurement.

Need experiment that measures ν_e and $\nu_{\mu,\tau}$ separately.

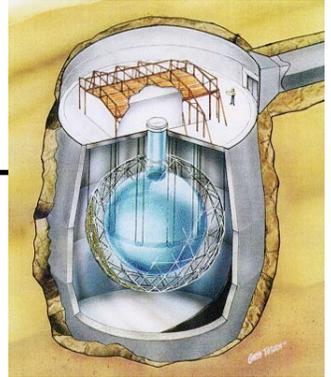




Construction of the Sudbury Neutrino Observatory

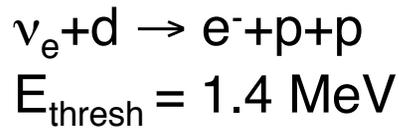


Neutrino Detection in SNO

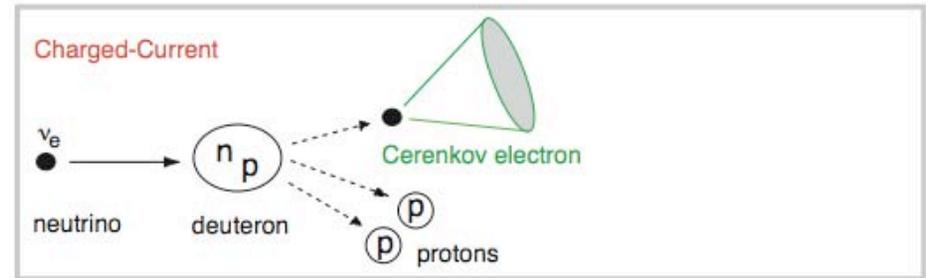


Neutrino Interactions on Deuterium and their Flavor Sensitivity

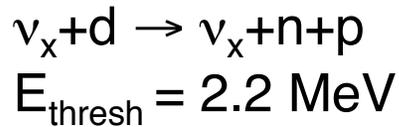
Charged-Current (CC)



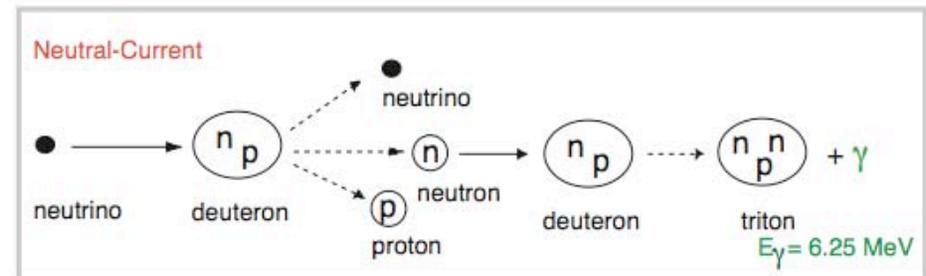
Measurement of energy spectrum



Neutral-Current (NC)



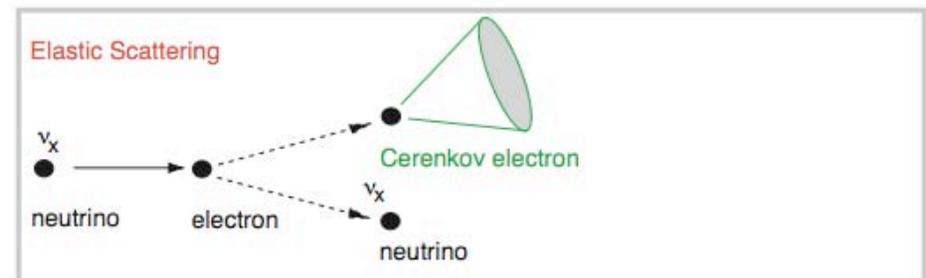
Measures total 8B flux from Sun



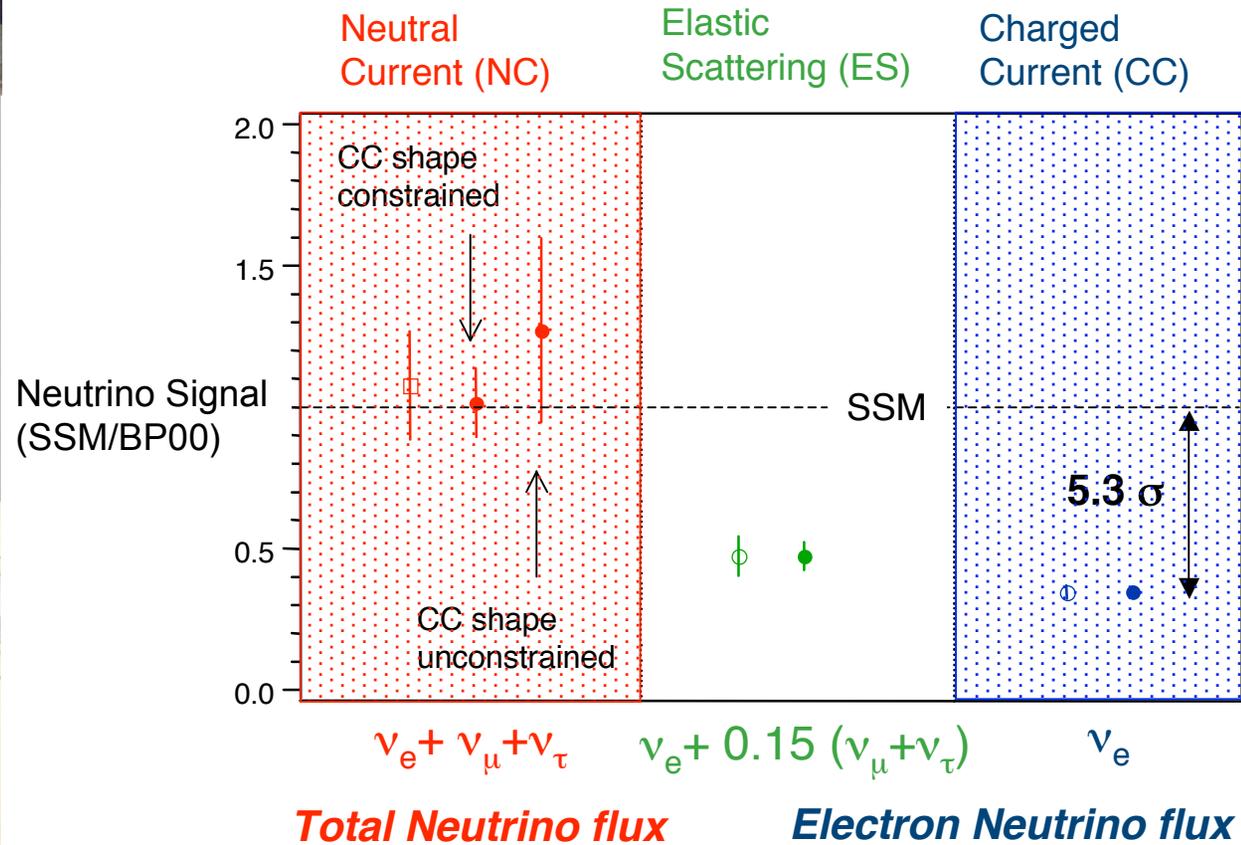
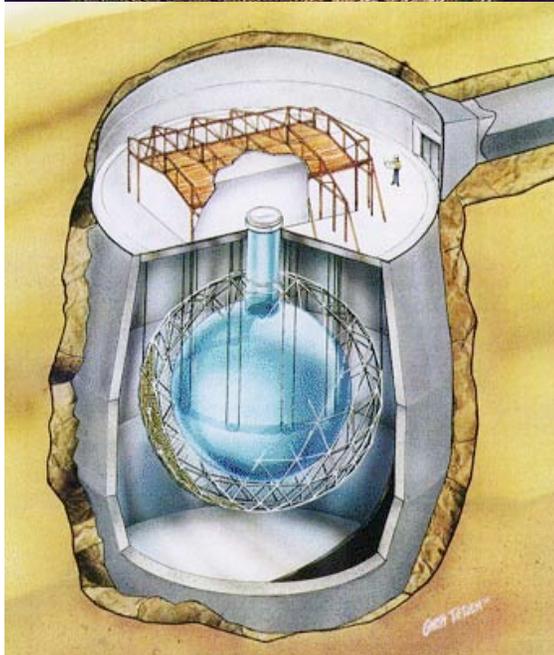
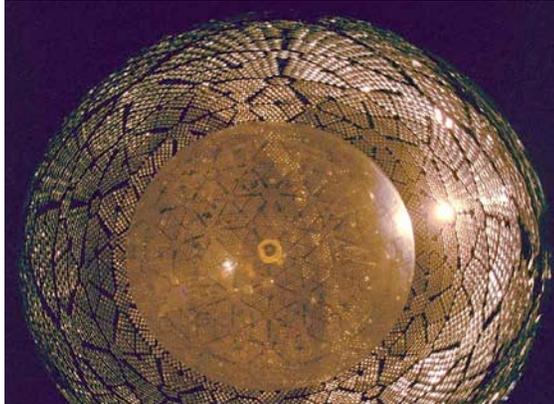
Elastic Scattering (ES)



Strong directional sensitivity



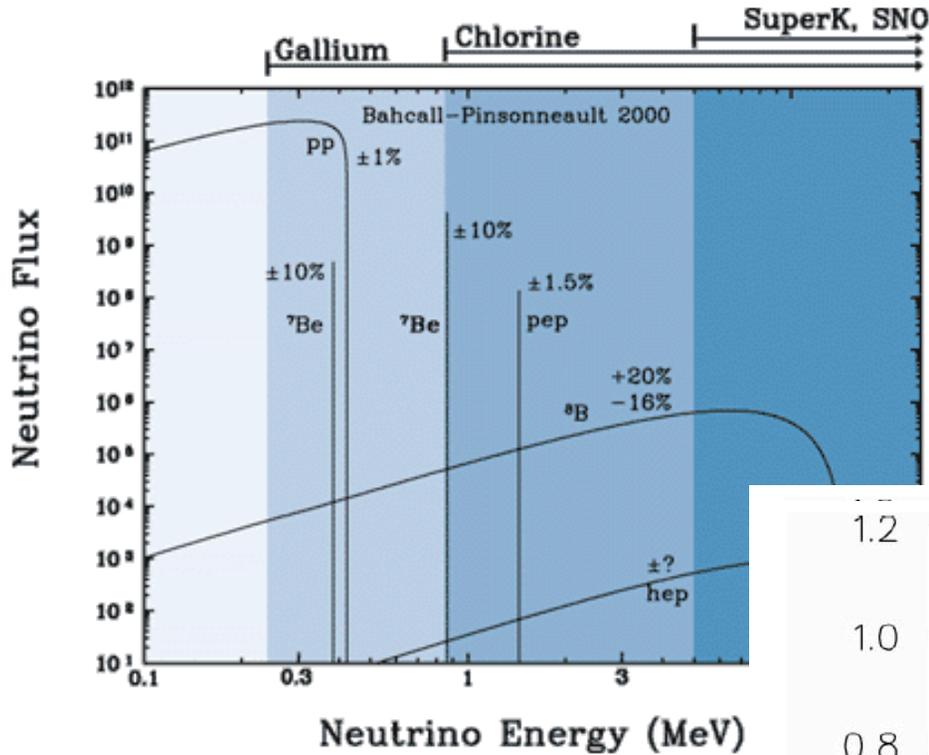
The Solution to the Solar Neutrino Problem: Neutrinos Change Flavor



Results from SNO, 2002

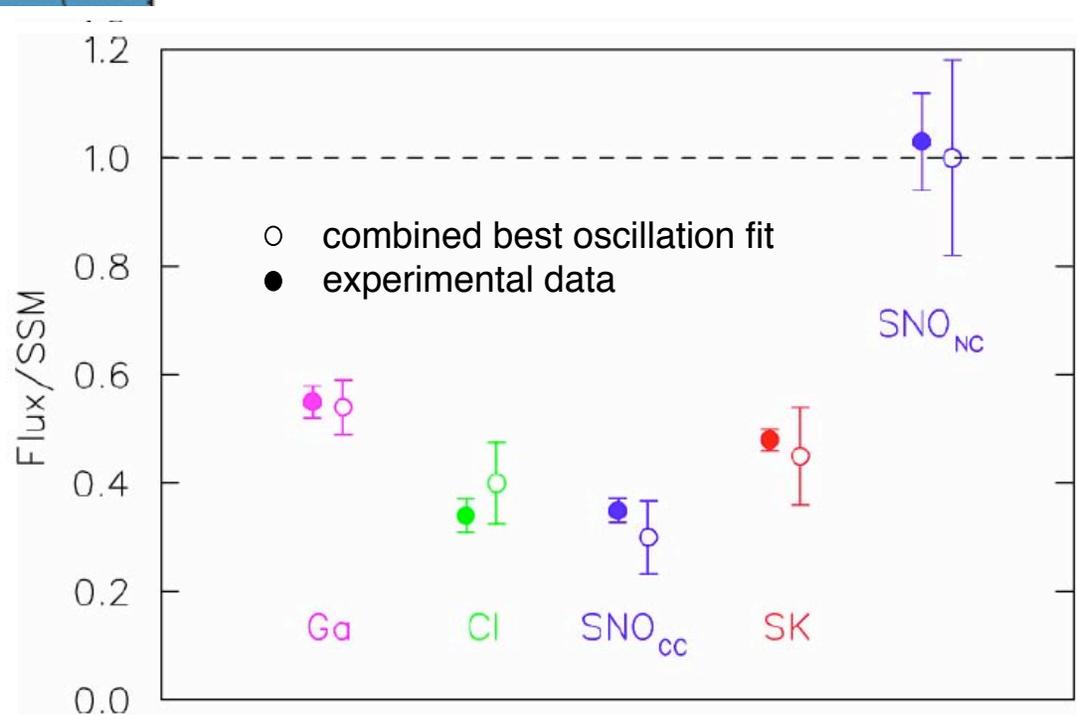
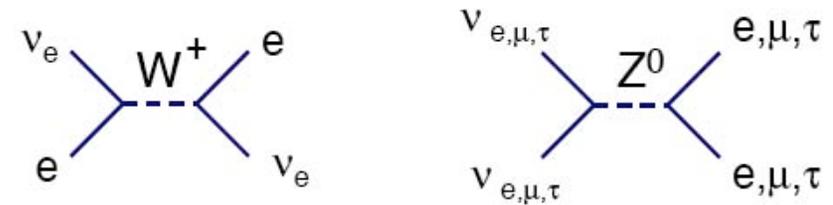
2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$

Oscillation Interpretation of Solar Neutrino Data



Energy-dependent effect

Neutrinos interact with matter in Sun and Earth (MSW)



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{23} \times U_{13} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

hep-ph/0402025

Neutrino Oscillation Experiments

Reactor and Beamstop Neutrinos

$$\nu_\mu \Rightarrow \nu_s \Rightarrow \nu_e$$

Atmospheric and Reactor Neutrinos

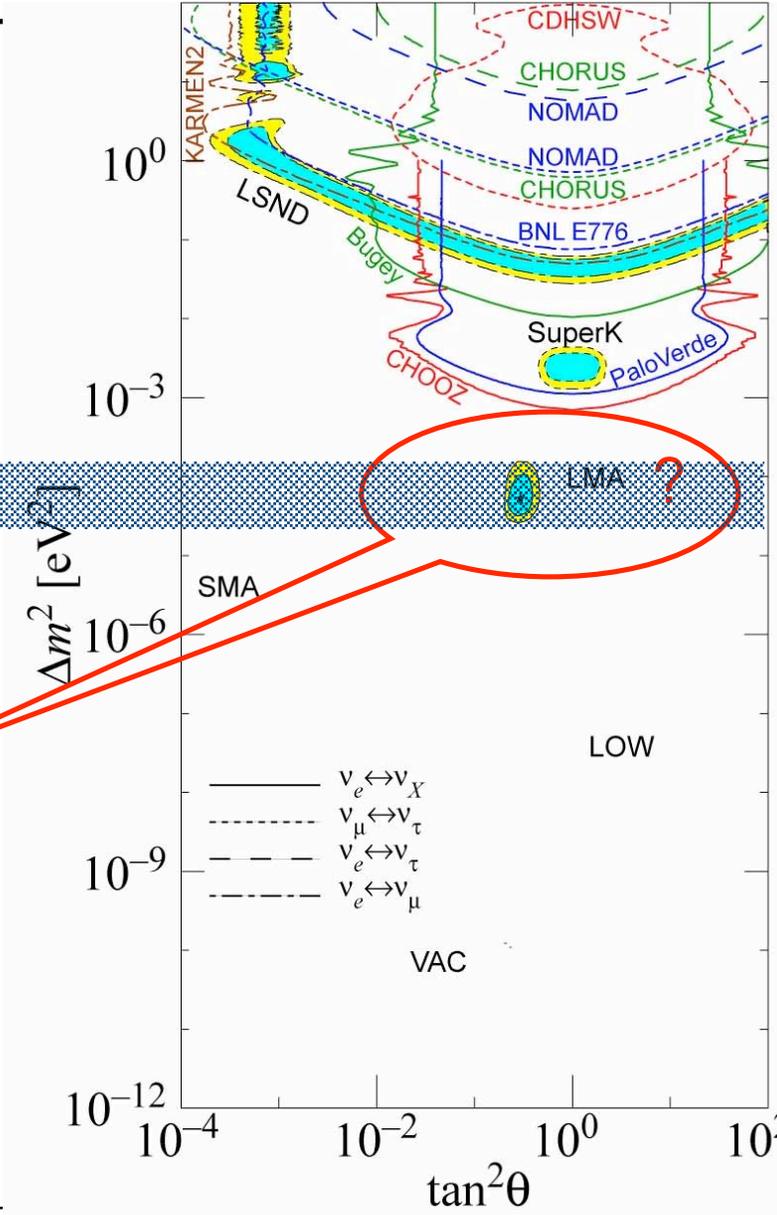
$$\nu_\mu \Rightarrow \nu_\tau$$

Solar and Reactor Neutrinos

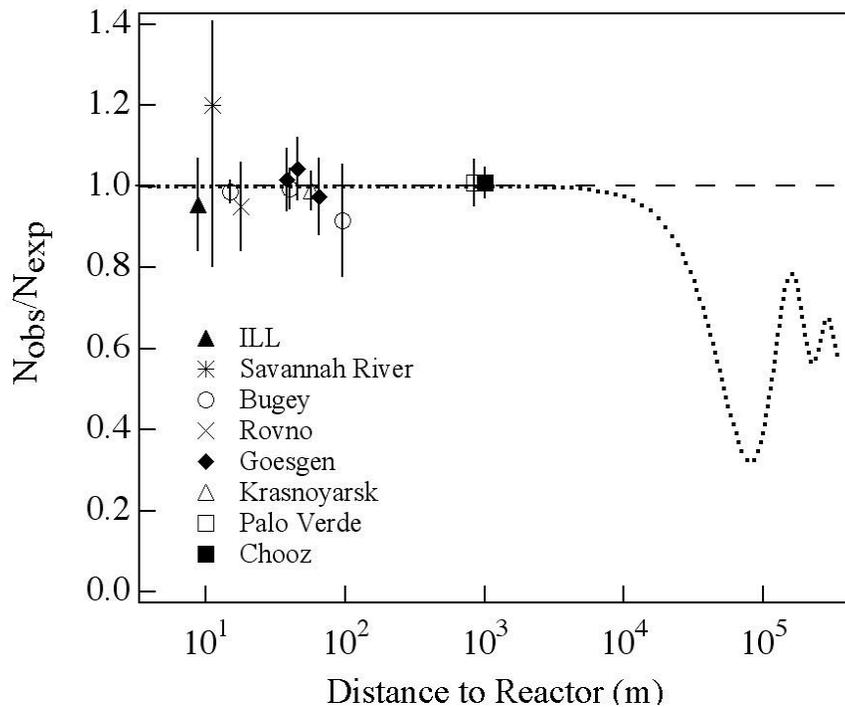
$$\nu_e \Rightarrow \nu_{\mu,\tau}$$

Large mixing favored
***LMA** solution can be tested with reactor neutrinos*

Status: Summer 2002



Search for Neutrino Oscillations with Reactor Neutrinos



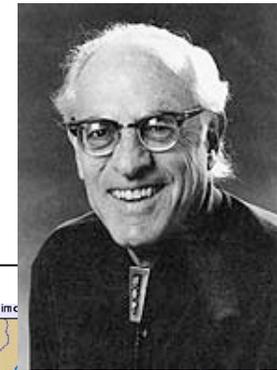
50 Years of Reactor Neutrino Physics

1953 First reactor neutrino experiment

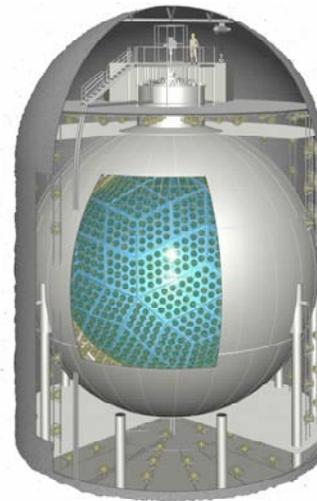
1956 "Detection of Free Antineutrino",
Reines and Cowan

→ Nobel Prize in 1995

No signature of neutrino
oscillations until 2002!



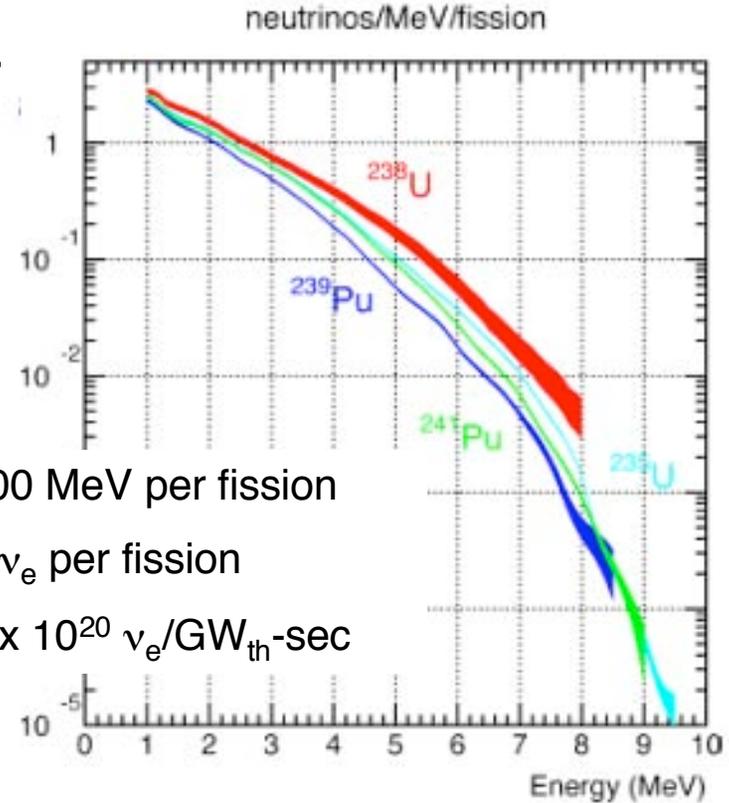
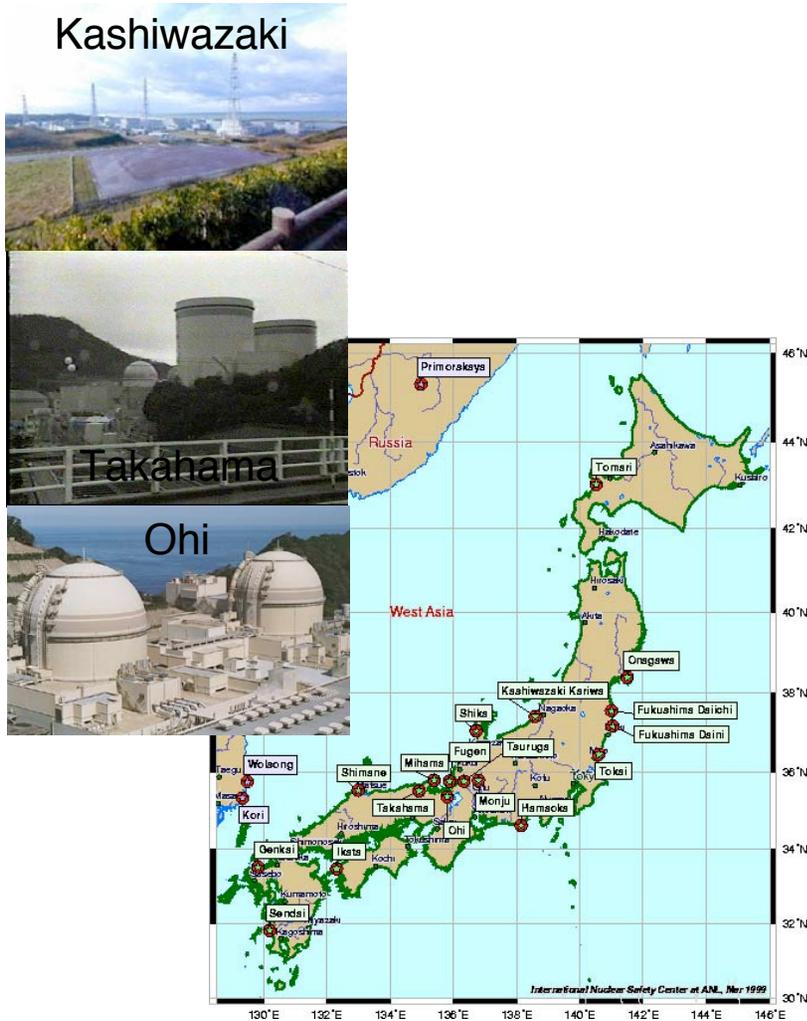
Results from solar experiments suggest
study of reactor neutrinos with a
baseline of ~ 70 km



Reactor Antineutrinos

Spectrum from Principal Reactor Isotopes

From Japanese Reactors

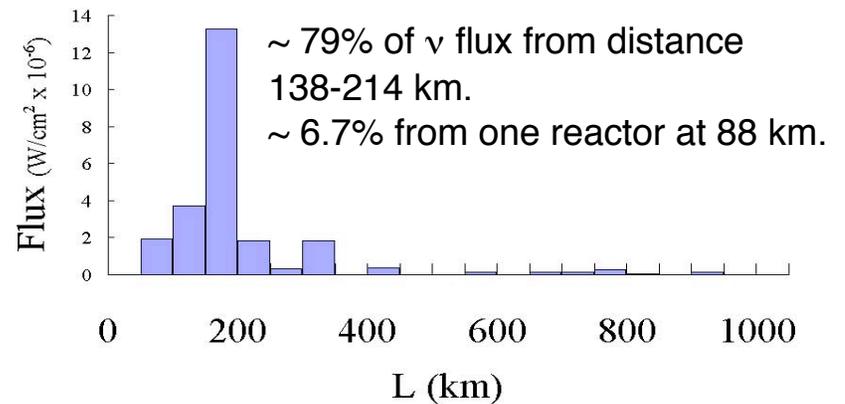


~ 200 MeV per fission

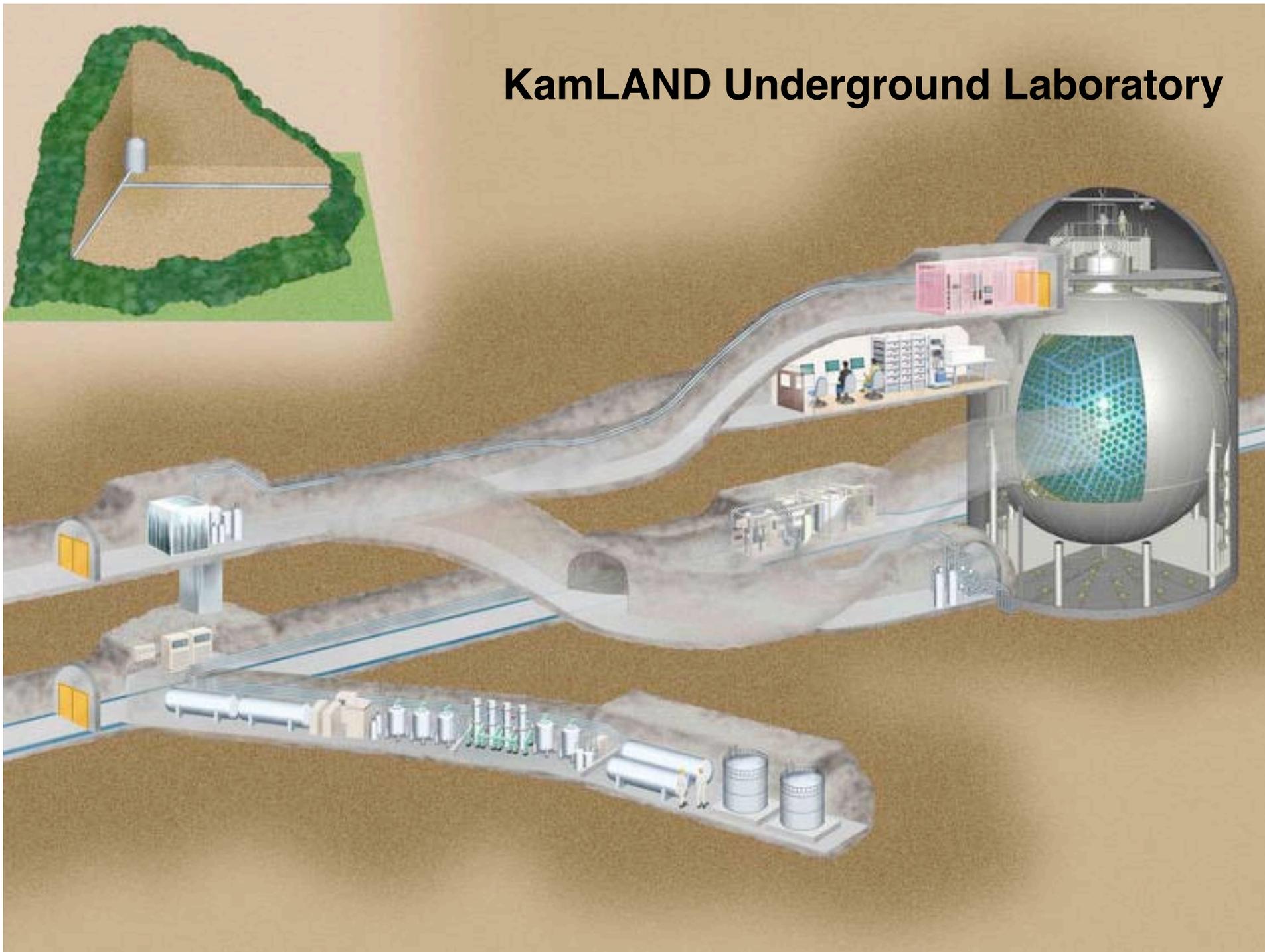
~ 6 ν_e per fission

~ $2 \times 10^{20} \nu_e/\text{GW}_{\text{th}}\text{-sec}$

Neutrino Flux at KamLAND



KamLAND Underground Laboratory



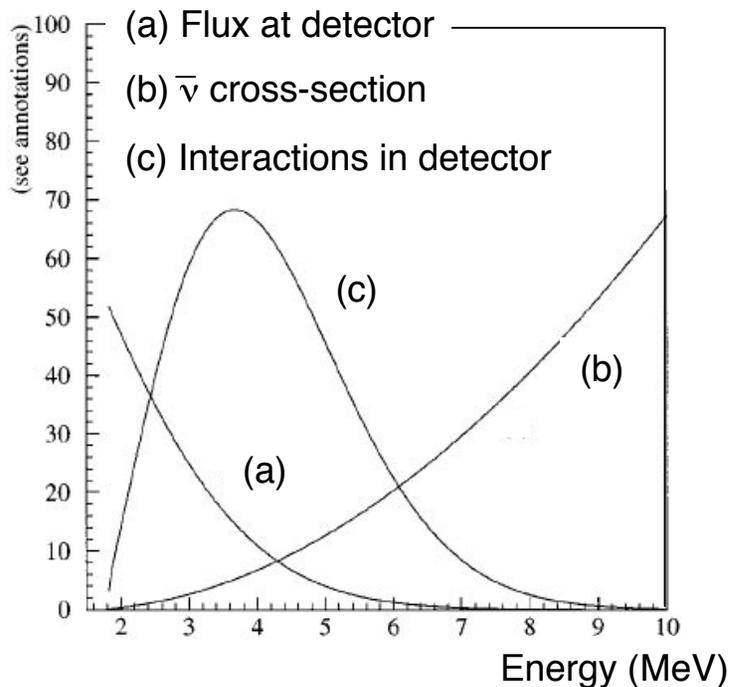
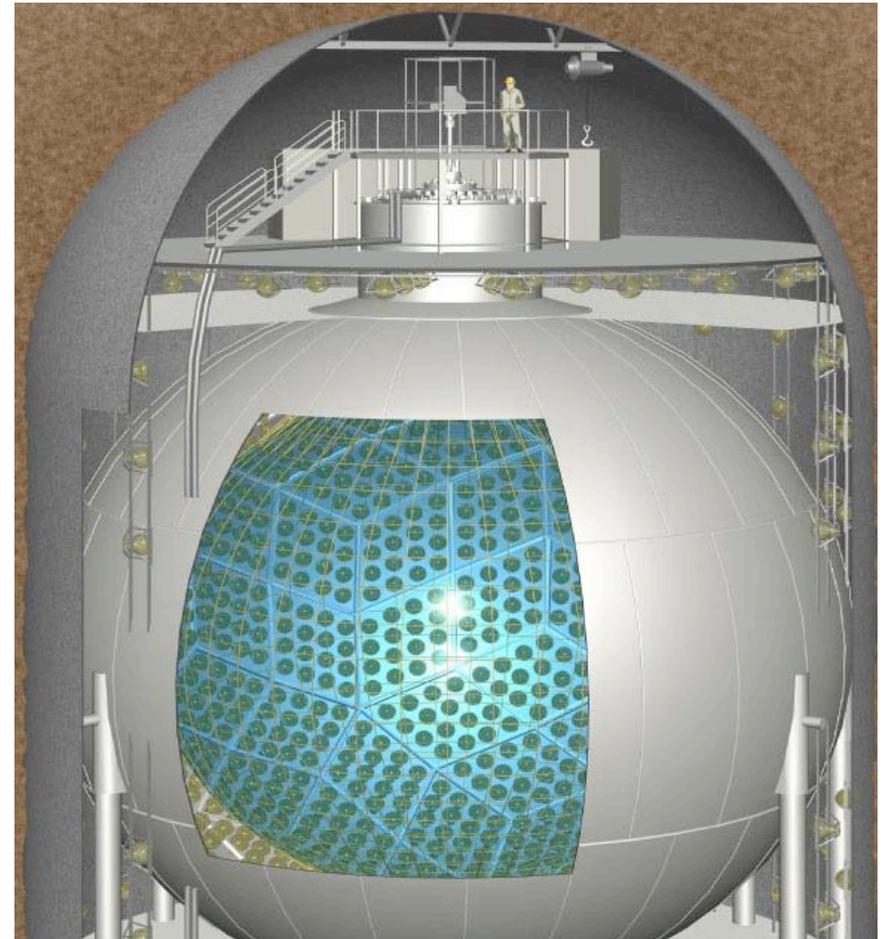
KamLAND - Kamioka Liquid Scintillator Antineutrino Detector

Uses reactor neutrinos to study $\bar{\nu}$ oscillation with a baseline of $L \sim 140\text{-}210$ km

Coincidence Signal: $\bar{\nu}_e + p \rightarrow e^+ + n$

Prompt e^+ annihilation

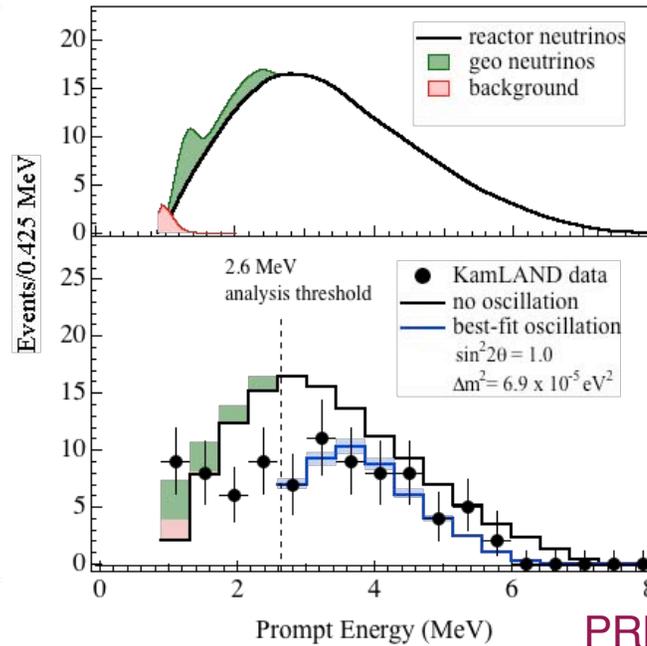
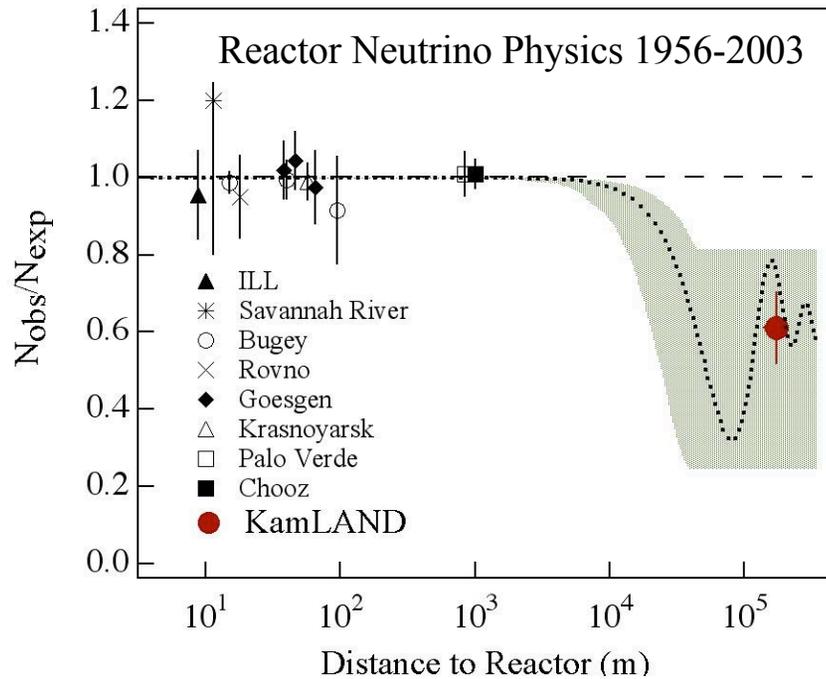
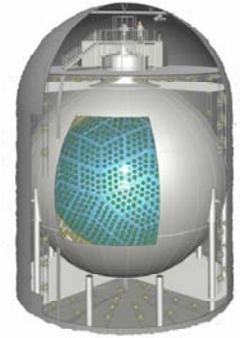
Delayed n capture, ~ 190 μs capture time



KamLAND studies the disappearance of $\bar{\nu}_e$ and measures

- interaction rate
- energy spectrum

First Direct Evidence for Reactor $\bar{\nu}_e$ Disappearance



PRL 90:021802, 2003

Observed

54 events

syst err. 6.4%

162 ton·yr, $E_{prompt} > 2.6 \text{ MeV}$

Expected

86.8 ± 5.6 events

Background

1 ± 1 events

accidental

0.0086 ± 0.0005

${}^9\text{Li}/{}^8\text{He}$

0.94 ± 0.85

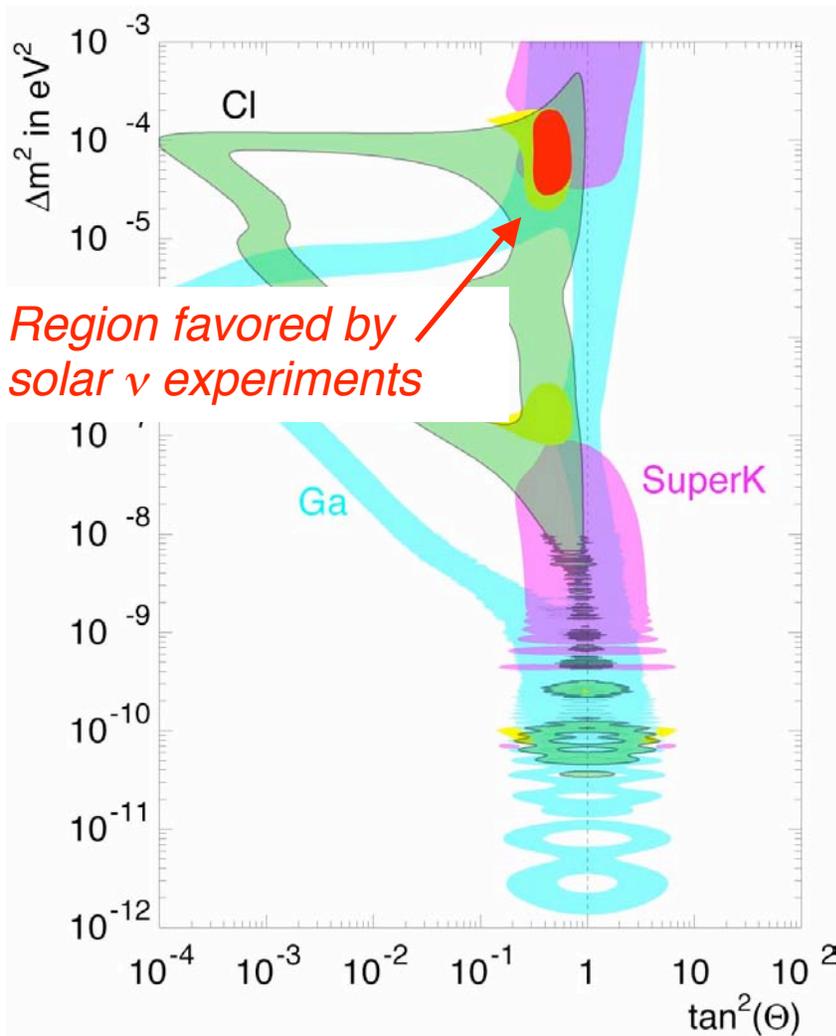
fast neutron

< 0.5

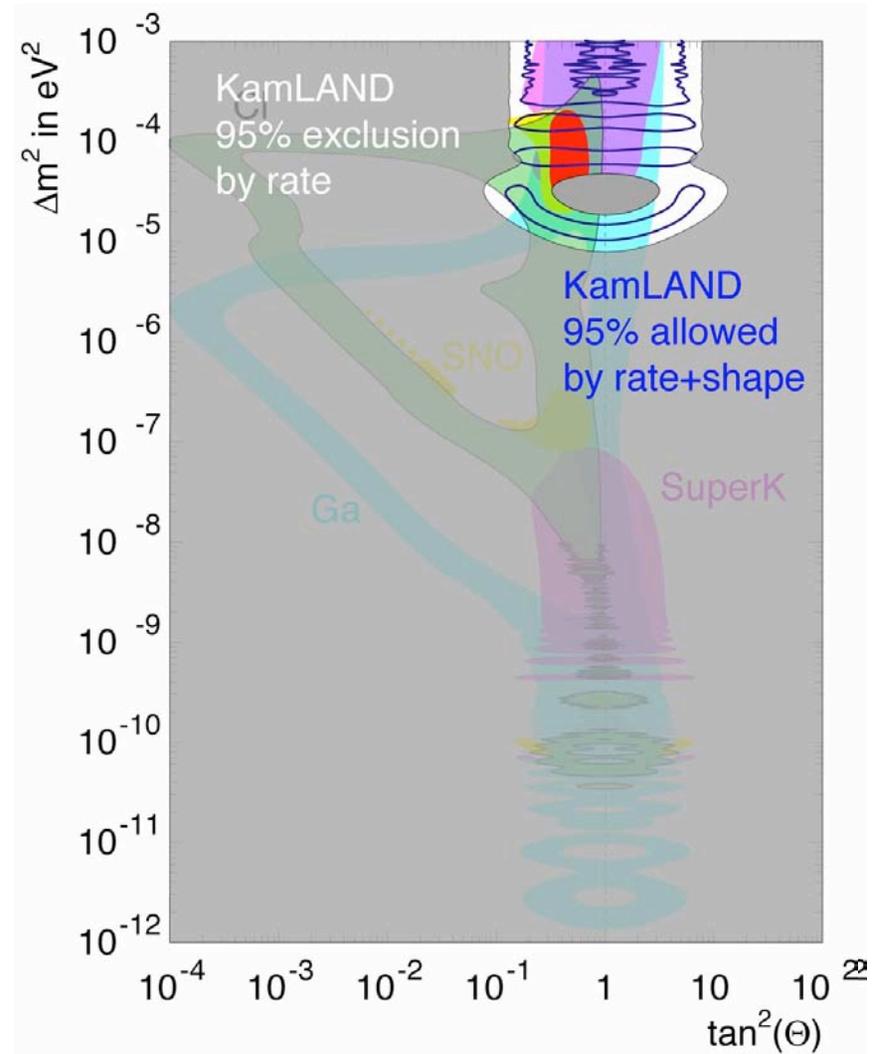
KamLAND provides evidence for neutrino oscillations together with solar experiments.

Oscillation Parameters *Before* and *After* KamLAND

Before KamLAND

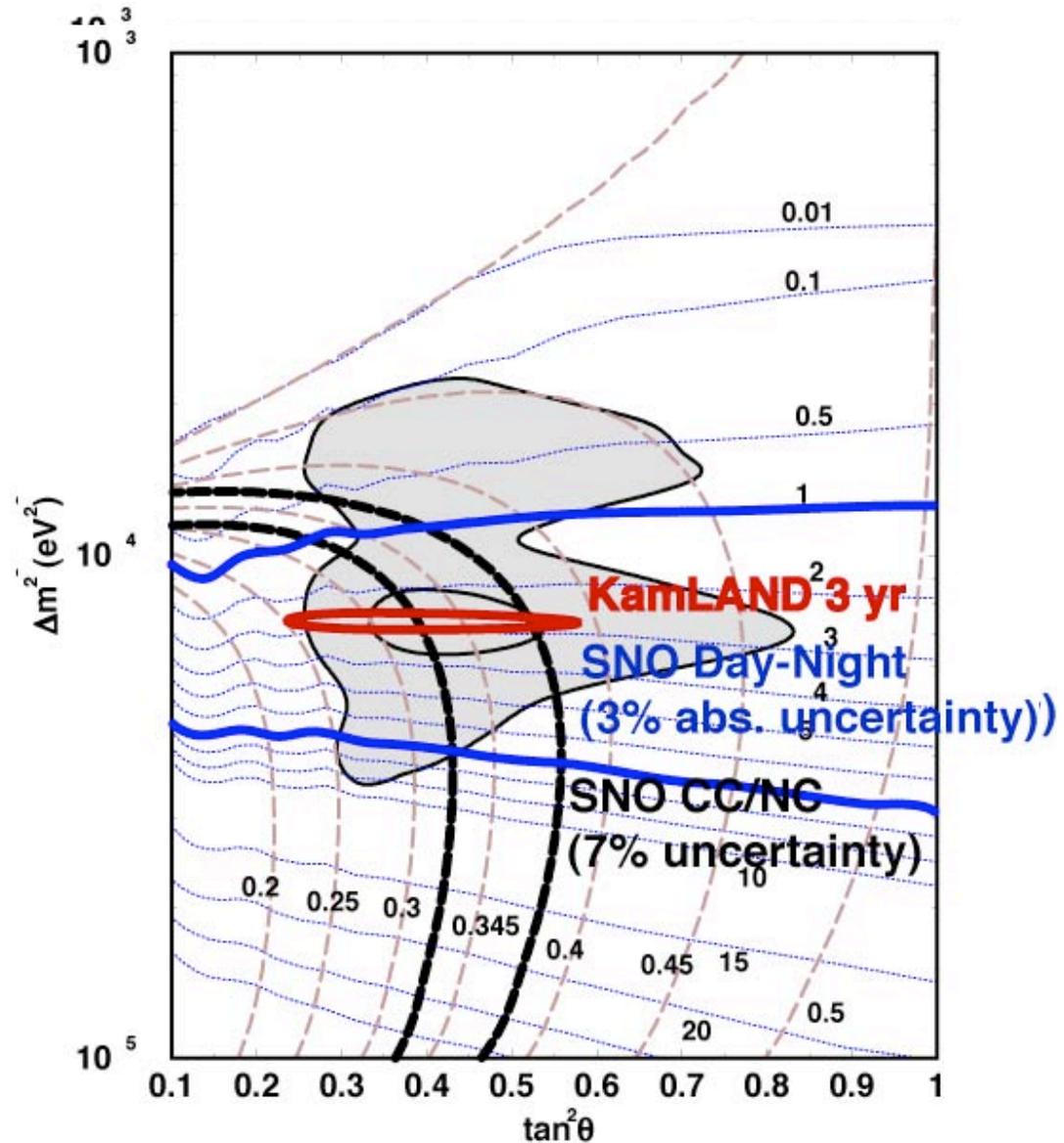


After KamLAND



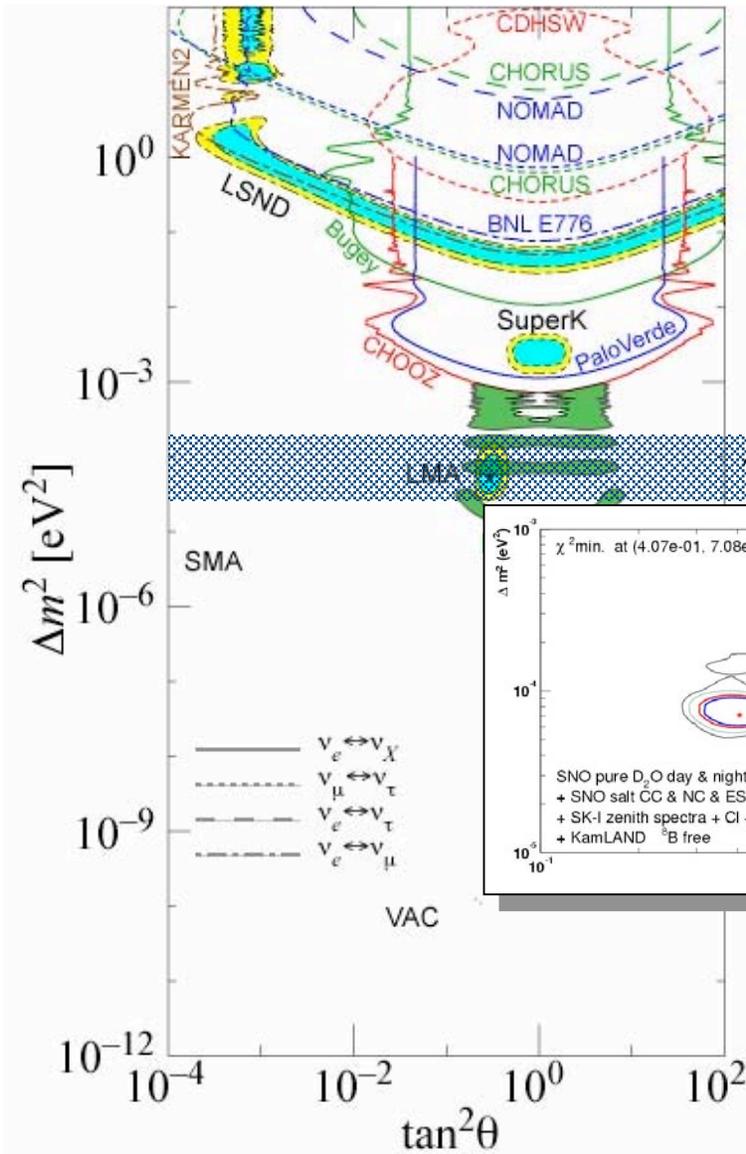
Defining θ_{12} , Δm_{12}^2 with SNO and KamLAND

Future Impact of Non-Accelerator Experiments on θ_{12} and Δm_{12}^2



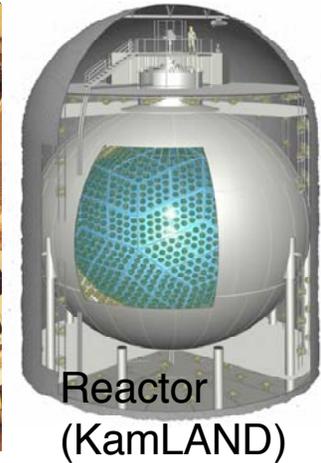
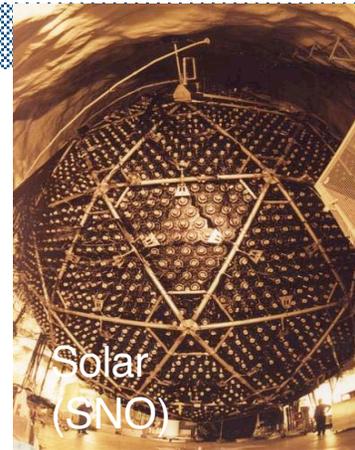
de Holanda et al., hep-ph/0212270,
Barger et al., hep-ph/0204253

Solar Neutrino Oscillations



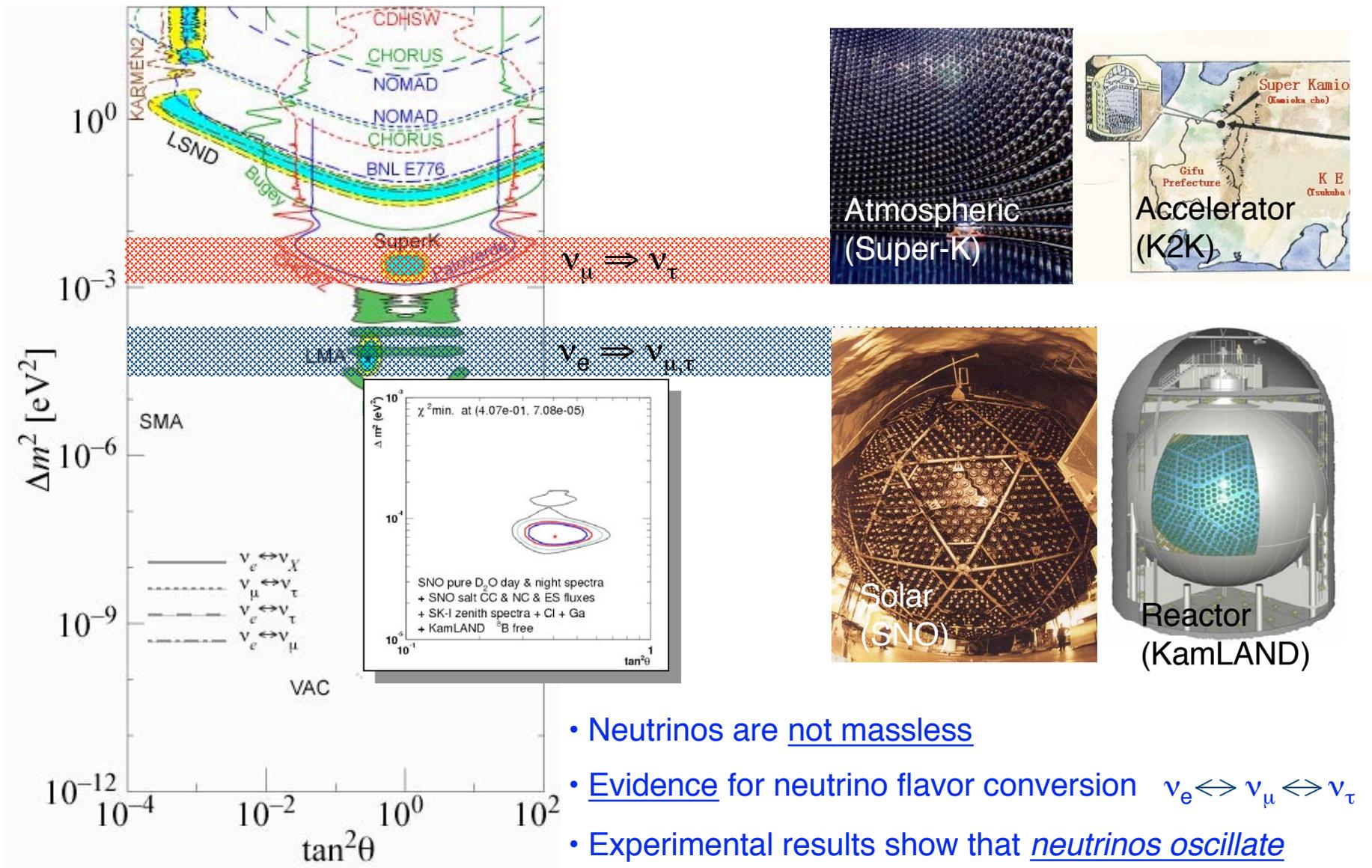
Flavor conversion of solar $\nu_e \rightarrow \nu_{\mu,\tau}$

mixing angle θ_{12} is large but not maximal,
 $\Delta m_{12} \sim 7 \times 10^{-5} \text{ eV}^2$



- matter effects enhance oscillation
- other modes for solar neutrino flavor transformation (sterile, RSFP, CPT ...) can play only a subdominant role.

Evidence for Mixing of Massive Neutrinos



- Neutrinos are not massless
- Evidence for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Experimental results show that neutrinos oscillate

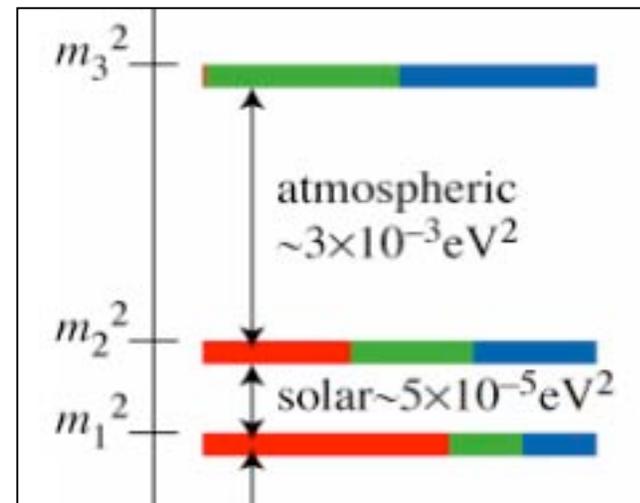
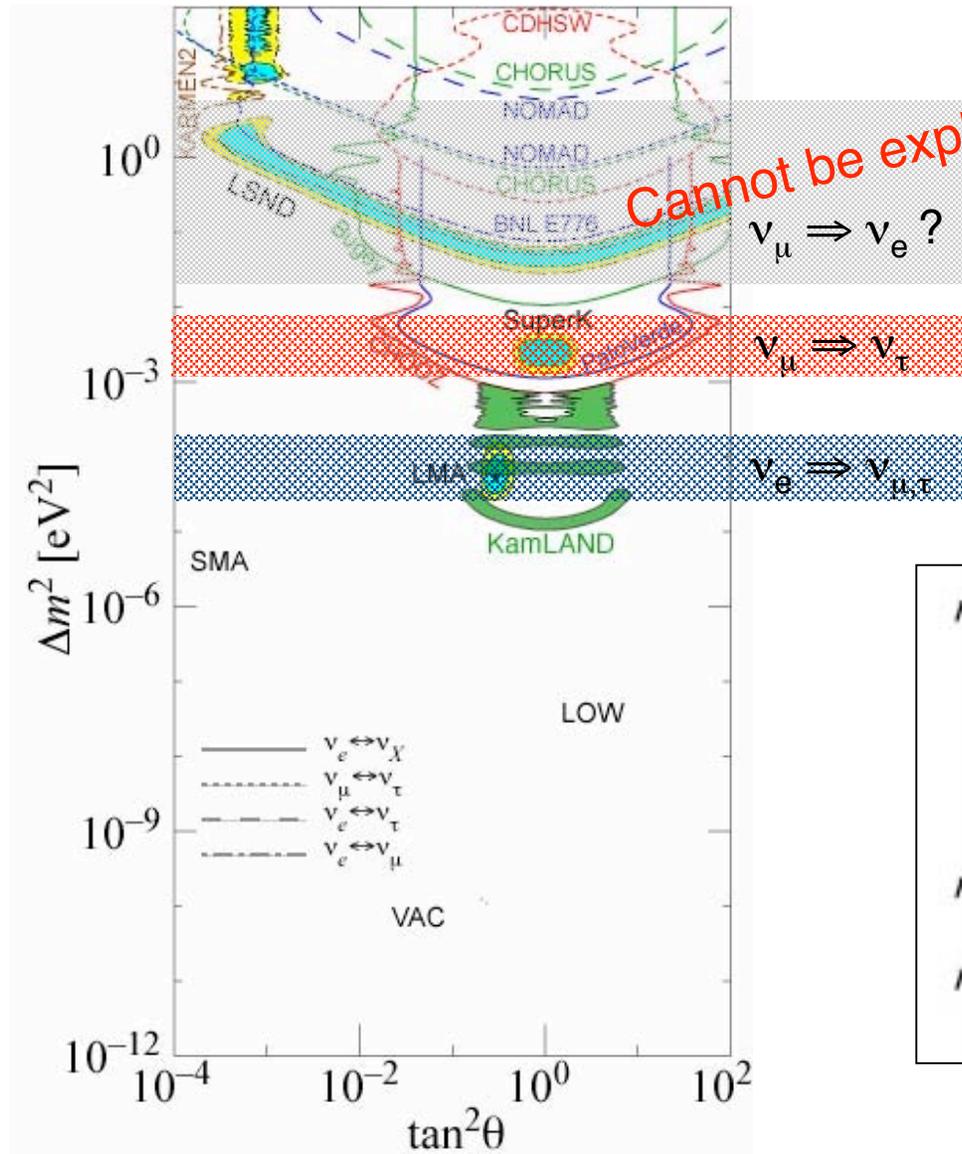
Other oscillations? Sterile Neutrinos?



LSND

Cannot be explained by 3 active neutrinos!

Will be checked by MiniBoone at FNAL (2005)



Cosmological Implications

Experimental Results

Atmospheric neutrinos: $\Delta m_{23}^2 \approx 2.0 \times 10^{-3} \text{ eV}^2$

\therefore one neutrino mass $> 0.04 \text{ eV}$

SNO + KamLAND: $\Delta m_{12}^2 \approx 7.3 \times 10^{-5} \text{ eV}^2$

\therefore one neutrino mass $> 0.008 \text{ eV}$

Limits on “ ν_e mass” give: $m(\nu_{1,2,3}) < 2.2 \text{ eV}$

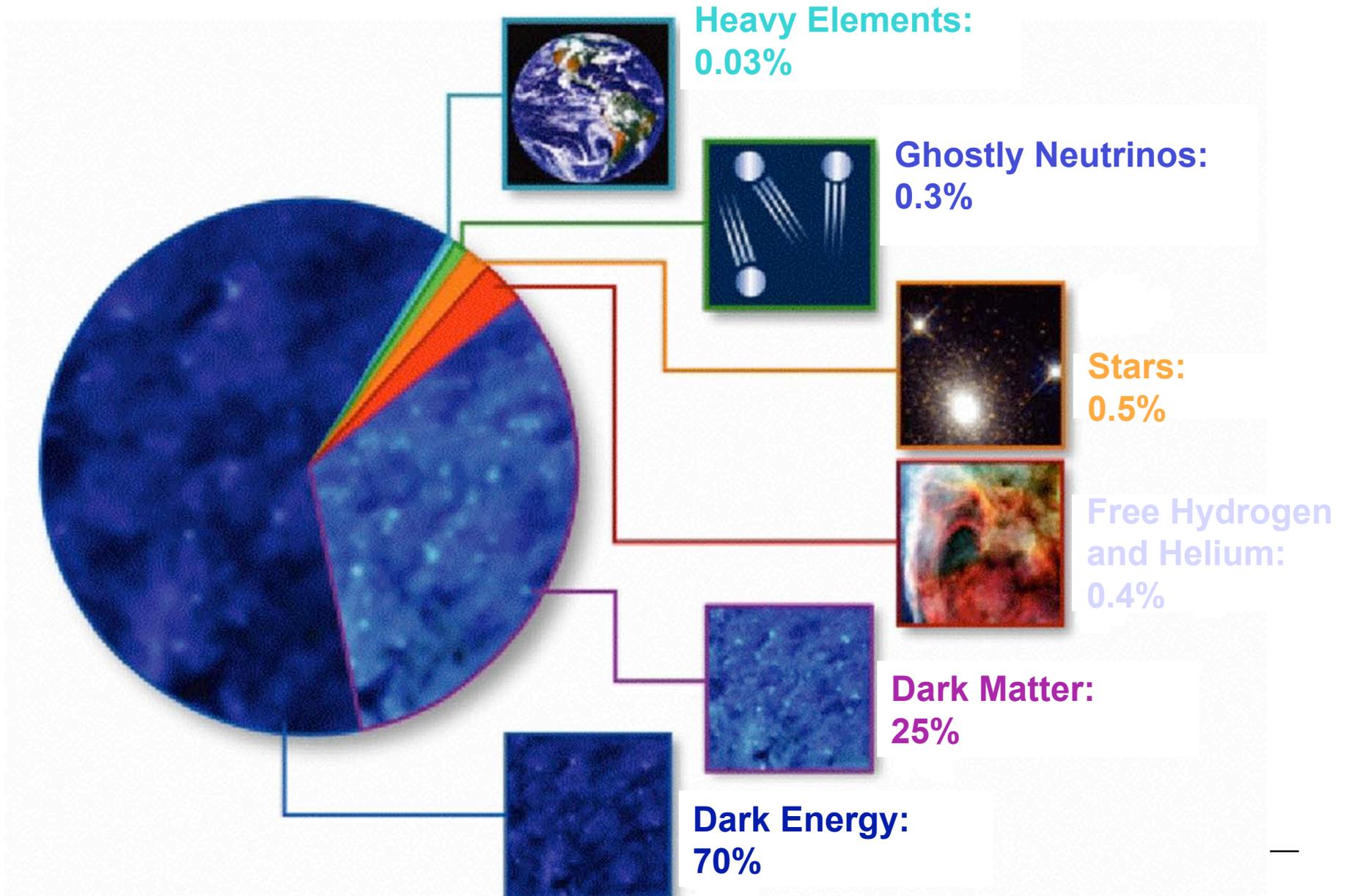
Implications

Σ of neutrino masses: $0.048 < m_1 + m_2 + m_3 < 6.6 \text{ eV}$

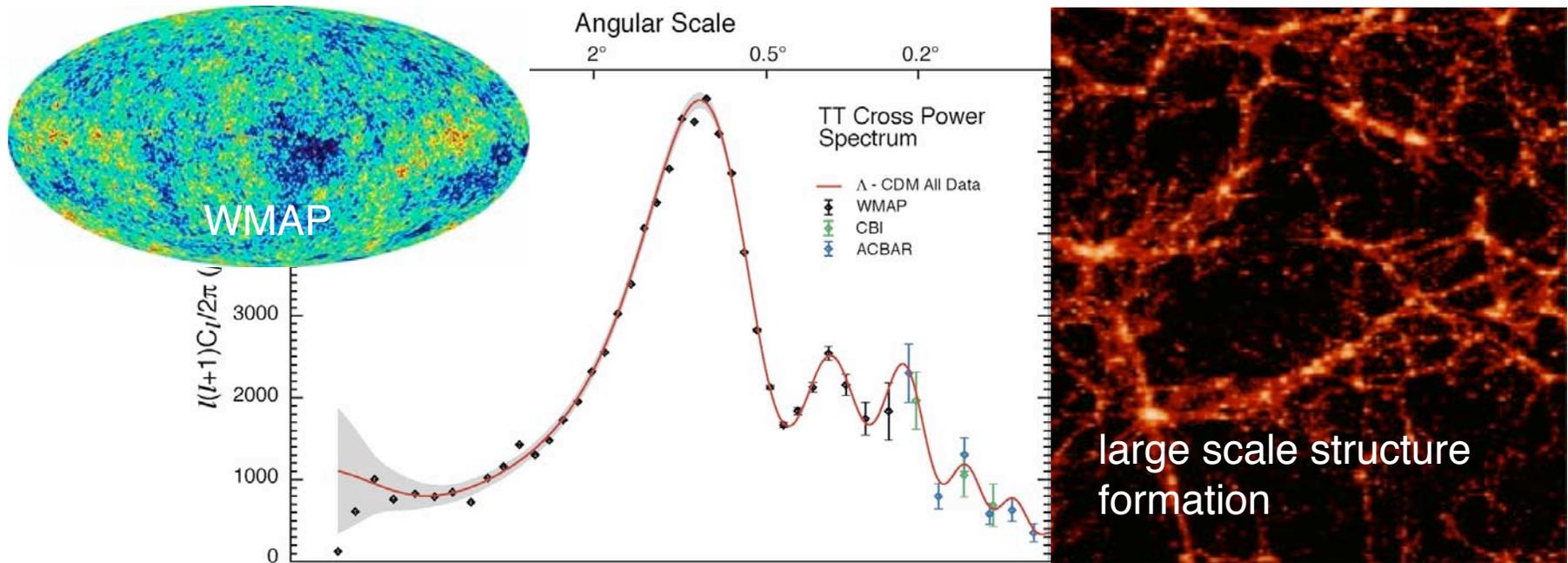
Laboratory limit on ν fraction of universe closure density: $0.001 < \Omega_\nu < 0.13$

Large-scale structure limit : $0.13 < \Omega_\nu < 0.02$

Matter in the Universe



Cosmological Information on Neutrino Mass



Neutrinos' contribution to the Universe's energy density

$$\Omega_\nu h^2 = \sum_i m_i / 95.3 \text{ eV}$$

Combining WMAP and large scale structure

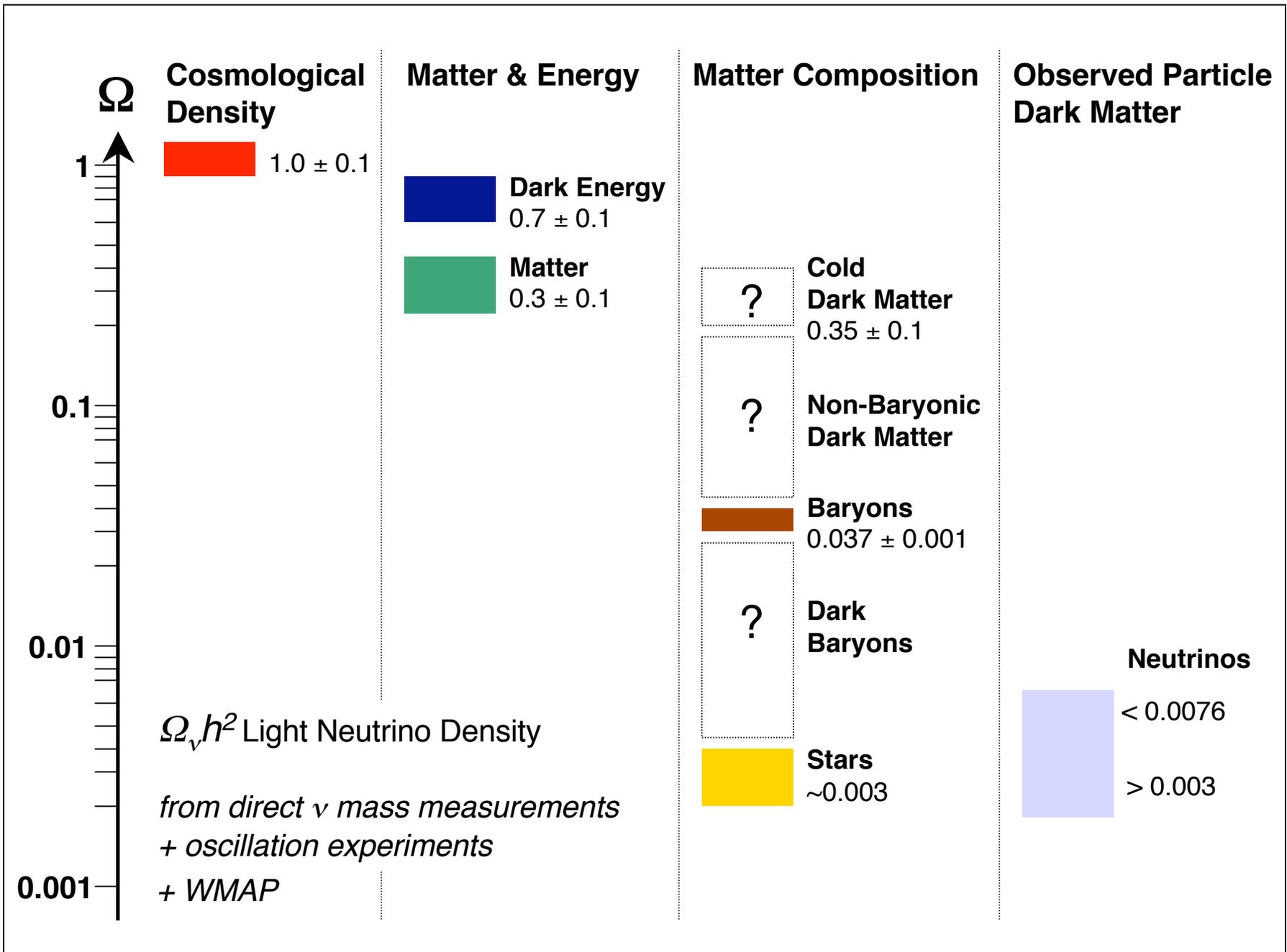
$$\Omega_\nu h^2 < 0.0076 \text{ eV (95\% CL)}$$

If $m_{\nu e} \sim m_{\nu \tau}$ (degenerate neutrino species)

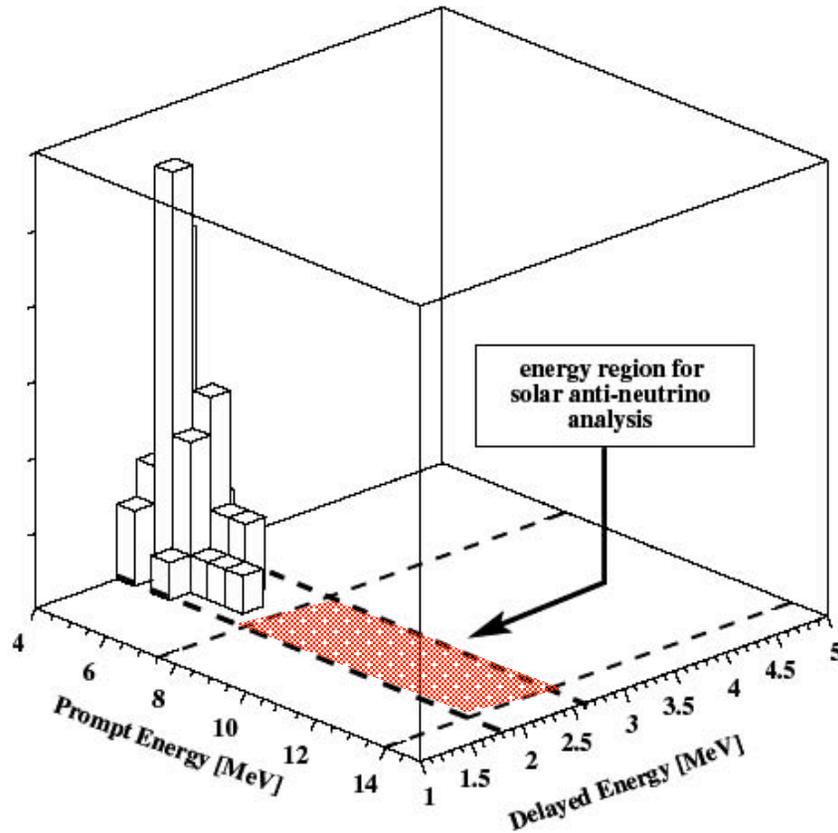
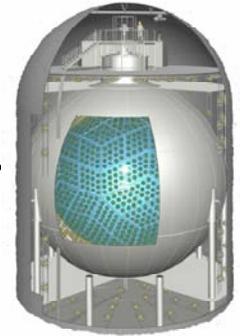
$$m_\nu < 0.23 \text{ eV}$$

Cosmological neutrino mass limits probe Dirac and Majorana ν masses!

Mass limits comparable to $0\nu\beta\beta$ experiments.



Search For Other Sources of High-Energy $\bar{\nu}$

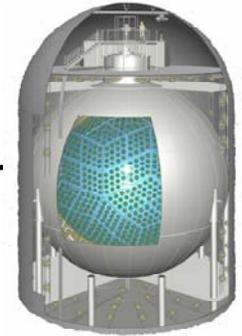


For $8.3 < E_{\bar{\nu}} < 14.8$ MeV,
no event was found in 185.5
live-days of data.

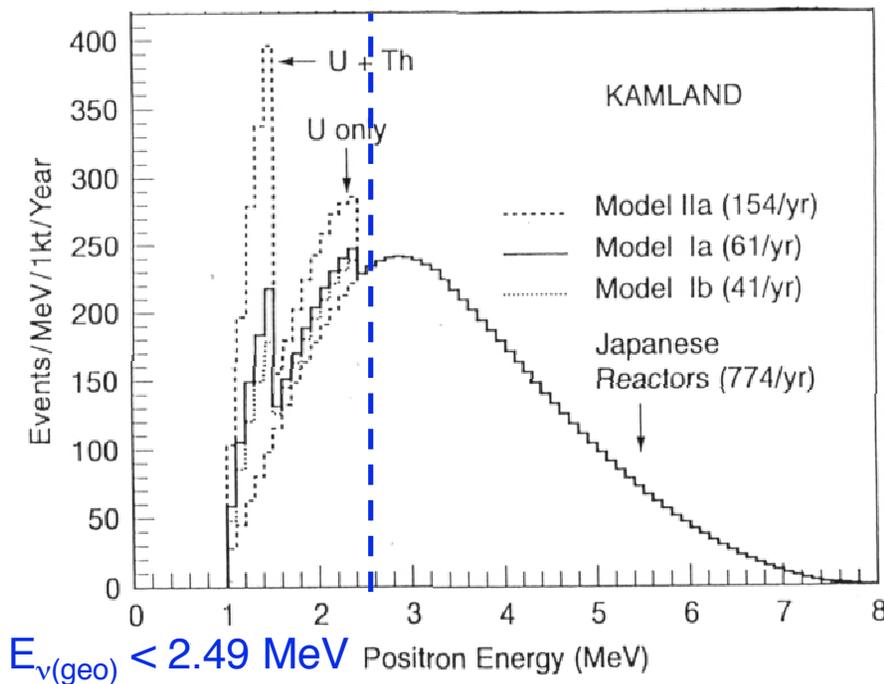
$$\Phi_{\bar{\nu}} < 3.7 \times 10^2 \text{ cm}^{-2}\text{s}^{-1} \text{ at 90\% CL}$$

assuming ν could come from
the Sun and has the same shape
as the undistorted ${}^8\text{B}$ ν spectrum.

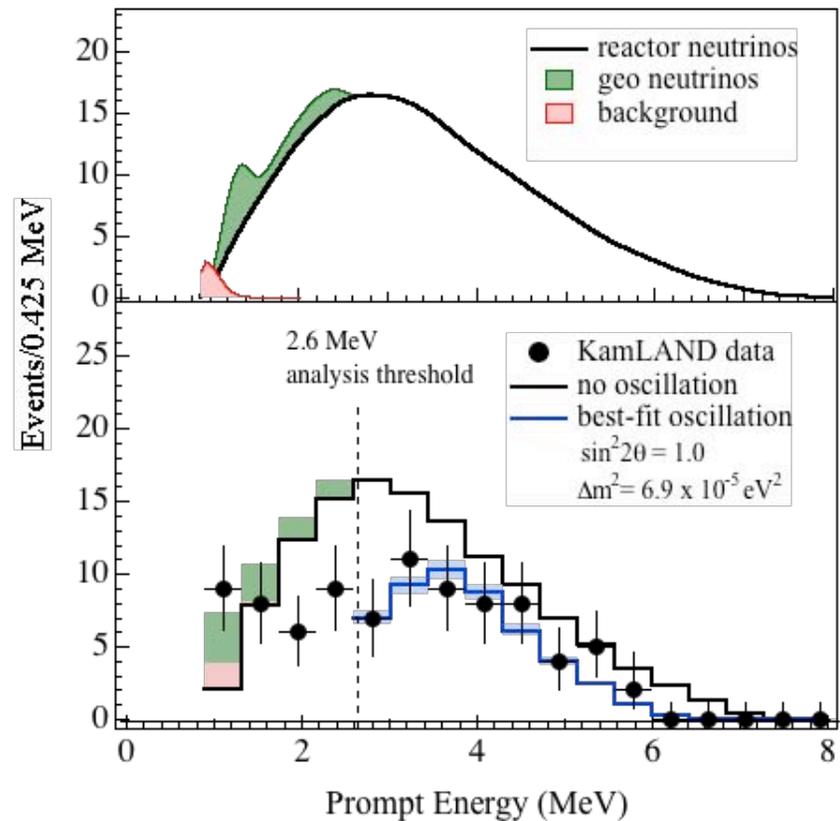
Search for a Geo-Neutrino Signal at KamLAND



Geophysics models assumes U/Th decays in the Earth produce radiogenic heat (40-60% of 40TW)



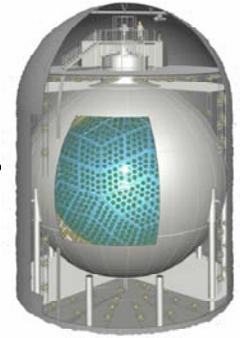
Raghavan et al. PRL 80 (1998)



KamLAND, PRL 90:021802, 2003

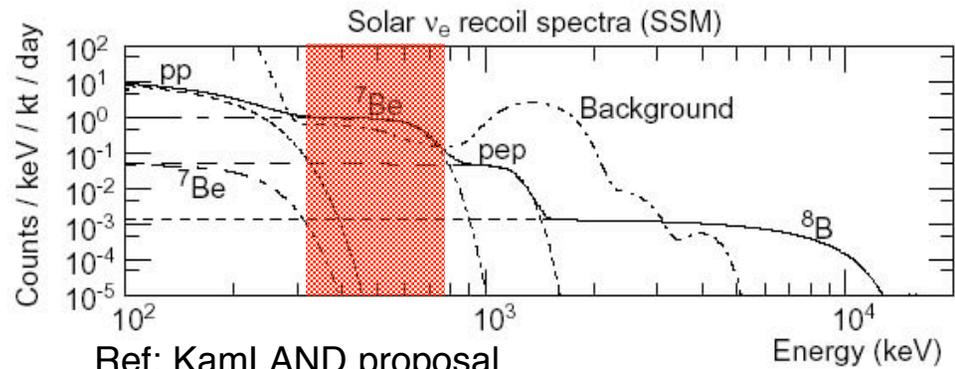
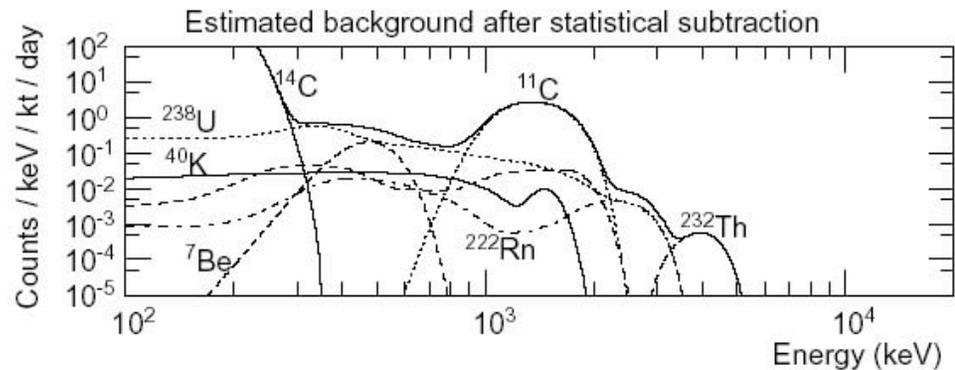
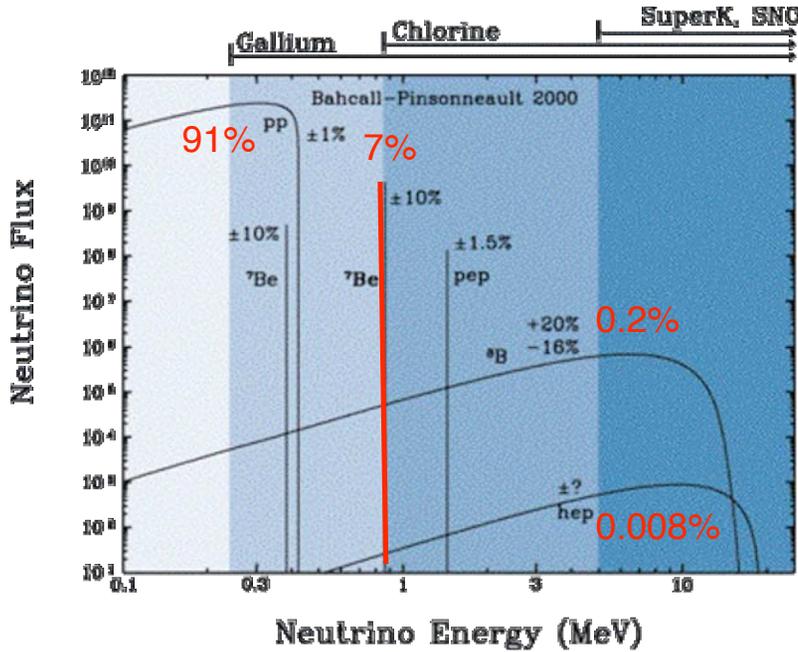
KamLAND can search for geo-neutrinos in spectrum. Stay tuned

Detecting ^7Be Solar Neutrinos at KamLAND



Direct detection of solar ^7Be neutrinos through elastic scattering

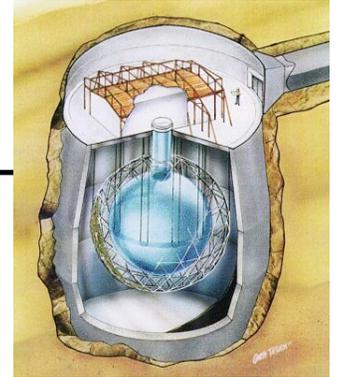
→ singles signal



Ref: KamLAND proposal

- ^7Be ν_e measurement can improve solar models.
- Unlikely to improve on θ_{12} .
- Checks oscillation prediction of ^7Be ν_e flux.

Nucleon Decay Limit from SNO



“Invisible Mode”

Motivation: $n \rightarrow 3\nu$ can become the dominant mode in certain grand unified theories

Mohapatra et al. Phys. Rev. D67, 075015 (2003)

- If a nucleon in ^{16}O decays “invisibly”, the resulting γ de-excitation of $^{15}\text{O}^*$ or $^{15}\text{N}^*$ would be visible

H. Ejiri Phys. Rev. C48, 1442 (1993)

- SNO has high-efficiency of observing $\sim 6\text{-}7$ MeV γ
→ looks like NC signal in SNO
- Compare detected neutron rates between D_2O and $\text{D}_2\text{O}+\text{salt}$ data, attribute difference to nucleon decay in ^{16}O

$\tau > 3.9 \times 10^{29}$ years (90% CL)

SNO, Phys. Rev. Lett., 92, 102004 (2004)

Open Questions in Neutrino Physics

- Is $U_{13} = 0$?
- Is there **CP violation** for neutrinos?
- What are the values of Δm^2 , U_{ij} ?
 - Future reactor and accelerator experiments
- Is U 3-dimensional? 4? 6? ∞ ?
 - or, is the 3-D version **unitary**?
 - or, are there **sterile** ν ?
 - MiniBoone
- What are the **absolute masses**?
- What is the level **ordering of 2,3 (or 1,3)**?
- Are ν 's **Dirac or Majorana** particles?
 - Direct mass measurements and $0\nu\beta\beta$

The most important things

Particle Properties

neutrino mass, hierarchy
& Dirac or Majorana

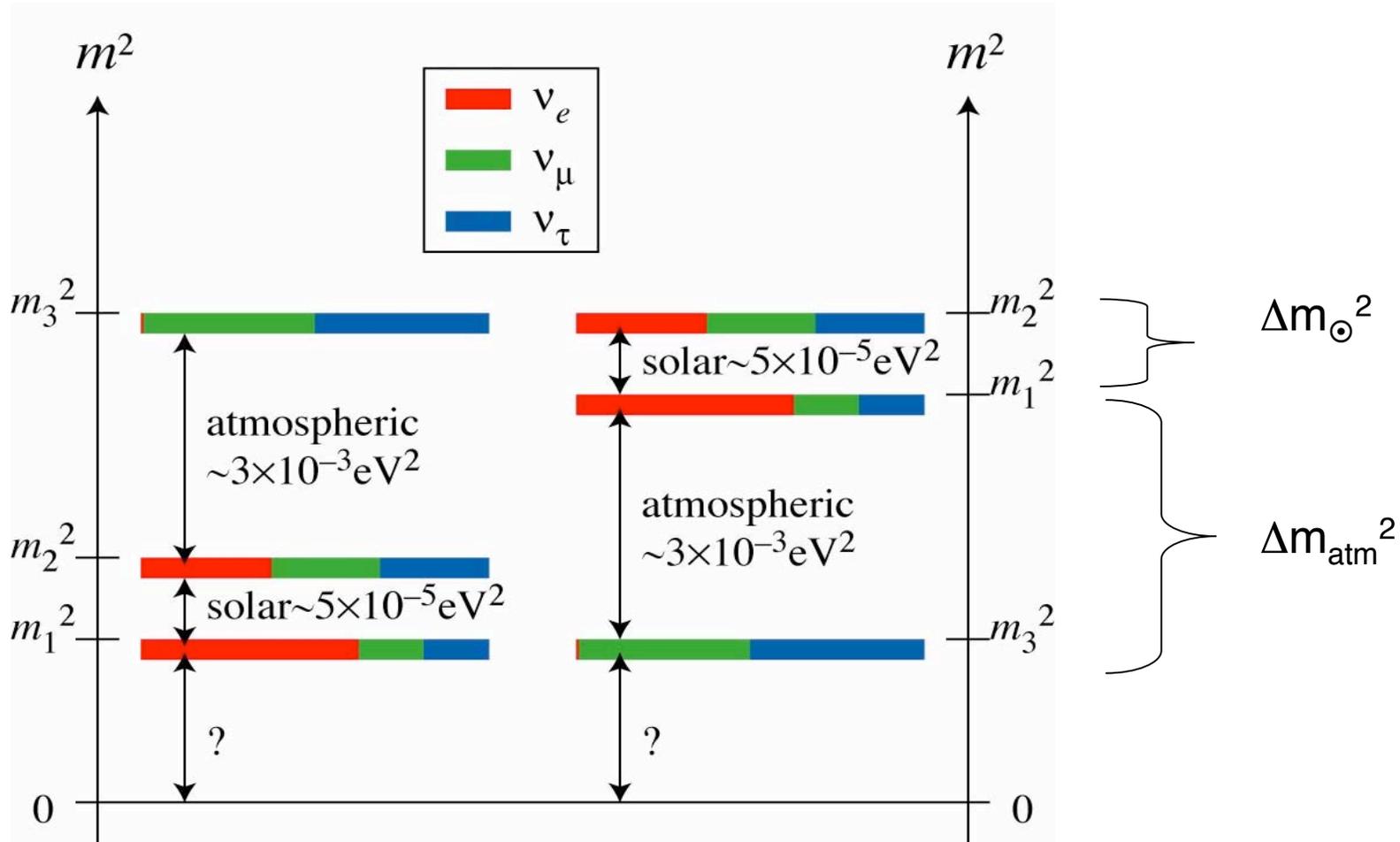
Oscillation Parameters

$\sin^2(2\theta_{13})$

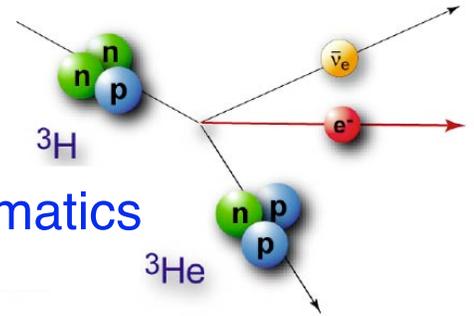
CP Violation

δ_{CP}

Neutrino Mass & Hierarchy



Direct Neutrino Mass Searches

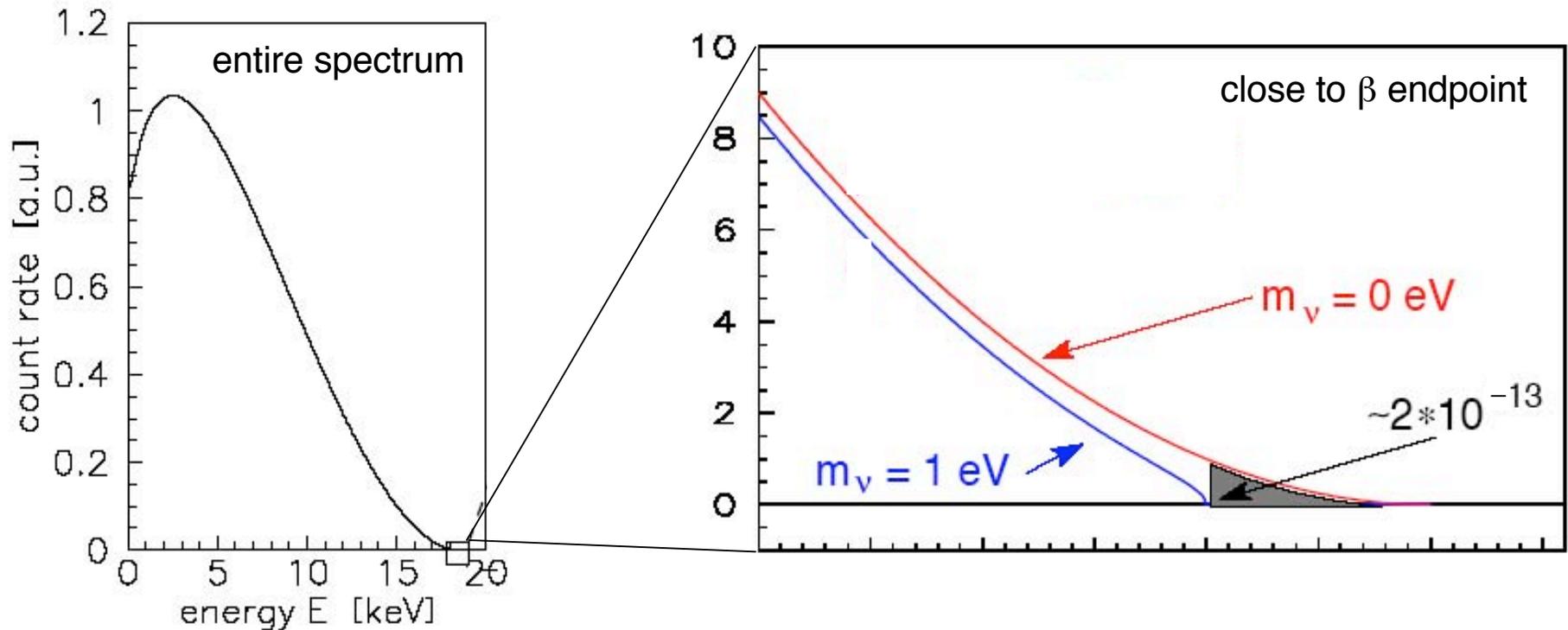


Model-Independent Neutrino Masses from β -decay Kinematics

$$N(E_e) \propto p_e E_e \underbrace{(E_0 - E_e)}_{E_\nu} \underbrace{\sqrt{(E_0 - E_e)^2 - m_\nu^2 c^4}}_{p_\nu}$$

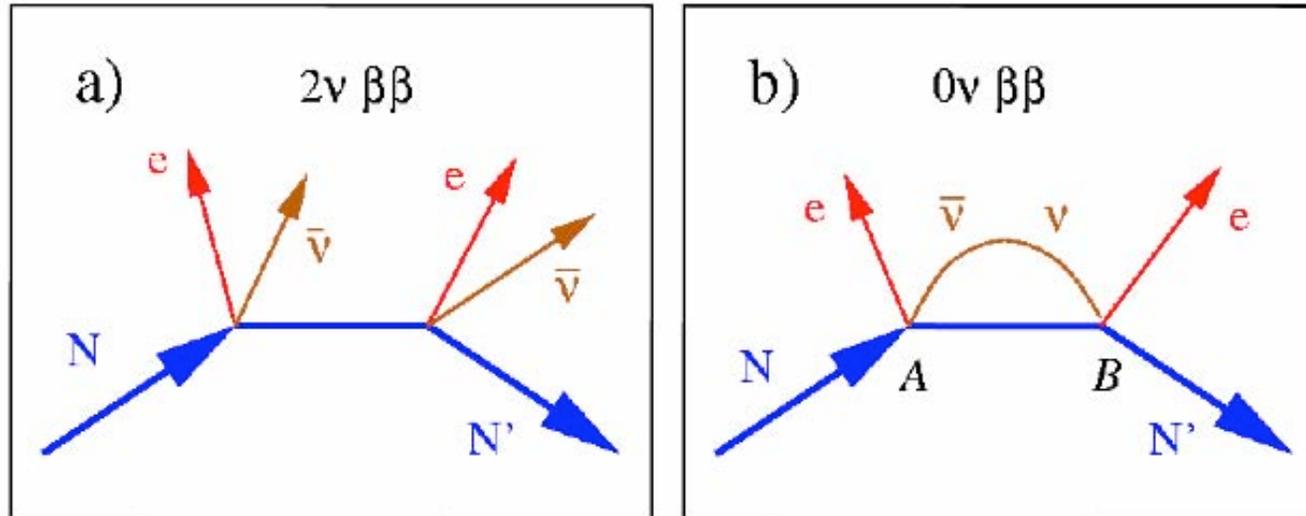
Current best limit $m_\nu < 2.2 \text{ eV}$

Search for a distortion in the shape of the β -decay spectrum in the end-point region



Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

The Next Frontier in Neutrino Physics



2ν mode: conventional 2nd order process in nuclear physics

0ν mode: hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

$$\Gamma_{2\nu} = G_{2\nu} |M_{2\nu}|^2$$

G are phase space factors

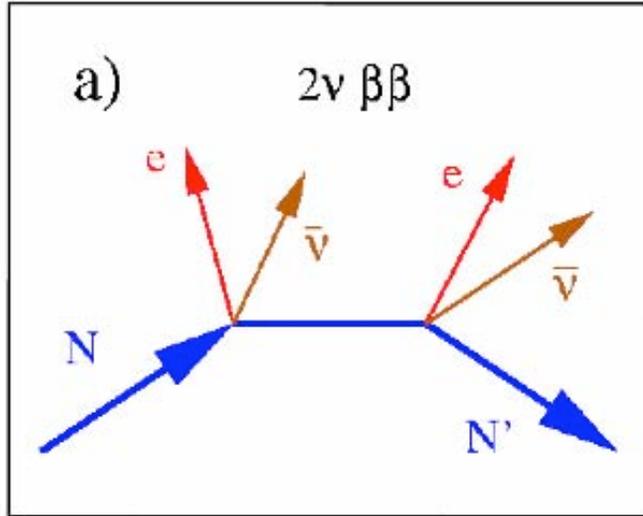
$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

$$G_{0\nu} \sim Q^5$$

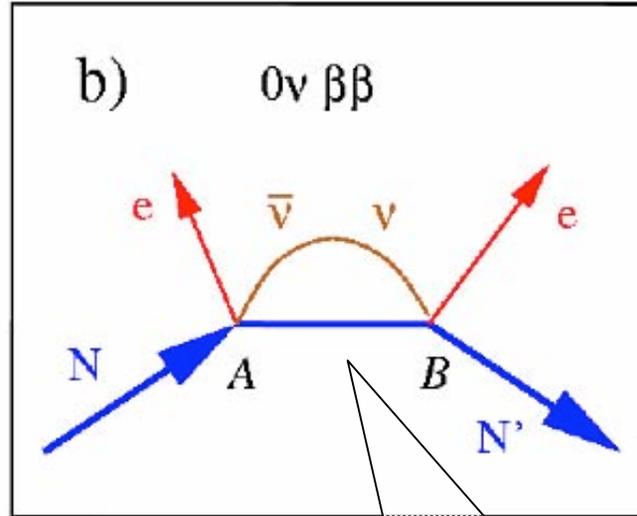
important physics

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

The Next Frontier in Neutrino Physics

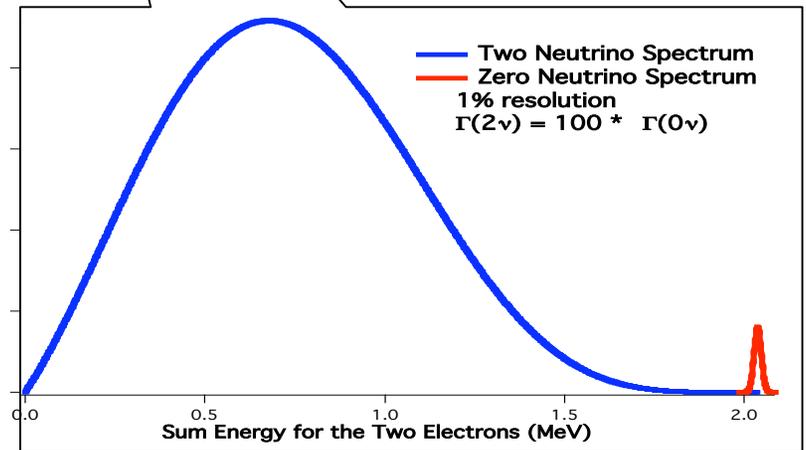


2ν mode: conventional 2nd order process in nuclear physics



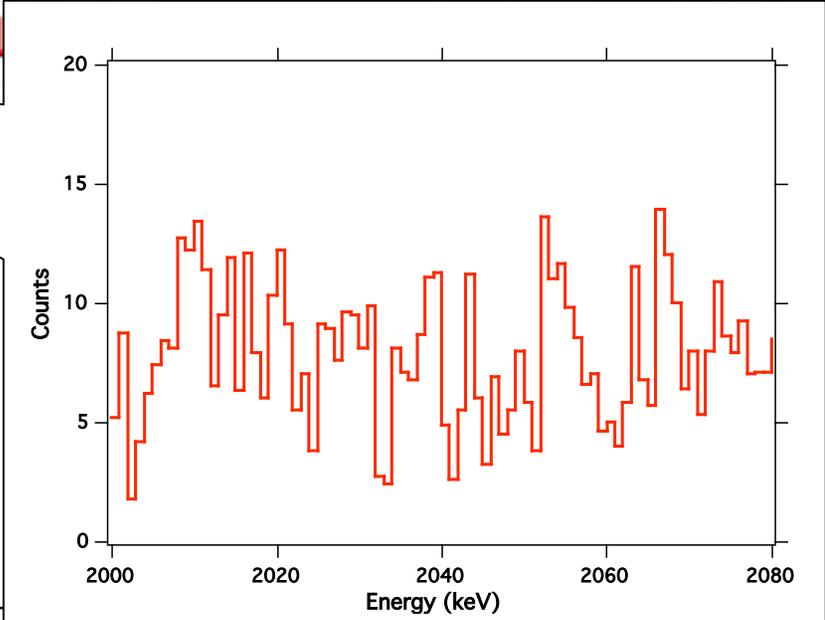
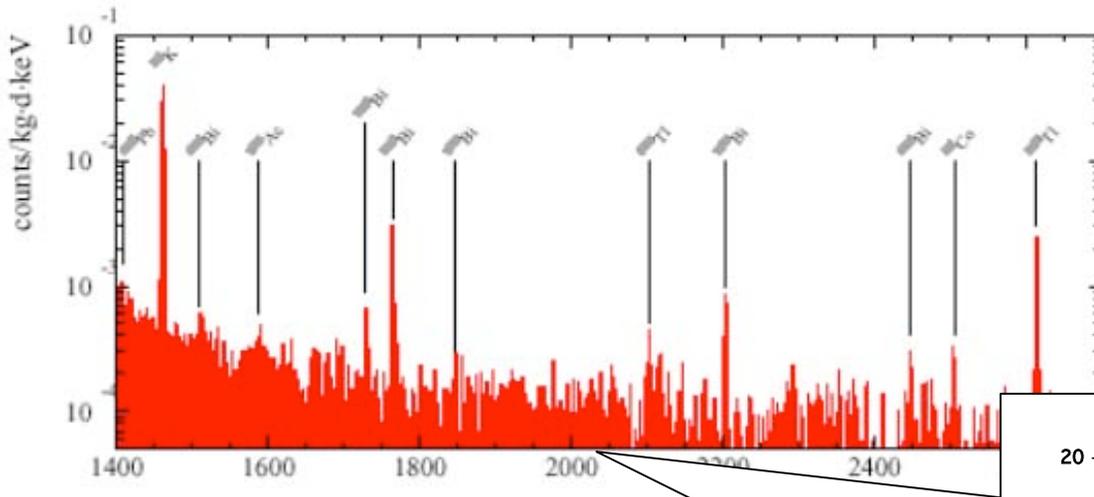
0ν mode: hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

The only known practical approach to discriminate Majorana vs Dirac ν



A Recent Claim for $0\nu\beta\beta$ in ^{76}Ge

5 detectors of overall 10.9 kg enriched to 86% in the $\beta\beta$ -emitter ^{76}Ge



$T = (0.8 - 18.3) \times 10^{25}$ years (95% C.L.)

Majorana ν Mass

$m_\nu = (0.05 - 0.84)$ eV 95% C.L.

$m_{\nu \text{ best}} = 0.39$ eV

The most important things

Particle Properties

neutrino mass, hierarchy
& Dirac or Majorana

Oscillation Parameters

$\sin^2(2\theta_{13})$

CP Violation

δ_{CP}

θ_{13} and ~~CP~~

U_{MNSP} Neutrino Mixing Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Dirac phase}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{\text{Majorana phases}}$$

atmospheric, K2K

$$\theta_{23} = \sim 45^\circ$$

maximal

reactor and accelerator

$$\tan^2 \theta_{13} < 0.03 \text{ at } 90\% \text{ CL}$$

small ... at best

SNO, solar SK, KamLAND

$$\theta_{12} \sim 32^\circ$$

large

$0\nu\beta\beta$

No good 'ad hoc' model to predict θ_{13} .
If $\theta_{13} < 10^{-3} \theta_{12}$, perhaps a symmetry?

θ_{13} yet to be measured
determines accessibility to CP phase

θ_{13} and ~~CP~~

U_{MNSP} Neutrino Mixing Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Dirac phase}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{\text{Majorana phases}}$$

atmospheric, K2K

reactor and accelerator

SNO, solar SK, KamLAND

$0\nu\beta\beta$

$$\theta_{23} = \sim 45^\circ$$

$$\tan^2 \theta_{13} < 0.03 \text{ at } 90\% \text{ CL}$$

$$\theta_{12} \sim 32^\circ$$

maximal

small ... at best

large

Amount of CP violation is given by $J_{\text{lepton}} \sim \underbrace{\cos^2(\theta_{13})}_{\sim 1} \underbrace{\sin(2\theta_{12})}_{\sim 0.9} \underbrace{\sin(2\theta_{23})}_{\sim 1} \sin(2\theta_{13}) \sin(\delta_{CP})$

Oscillation Measurements Probe Fundamental Physics

Physics at high mass scales, physics of flavor, and unification:

- Why are the mixing angles *large, maximal, and small*?
- Is there CP violation, T violation, or CPT violation in the lepton sector?
- Is there a connection between the lepton and the baryon sector?

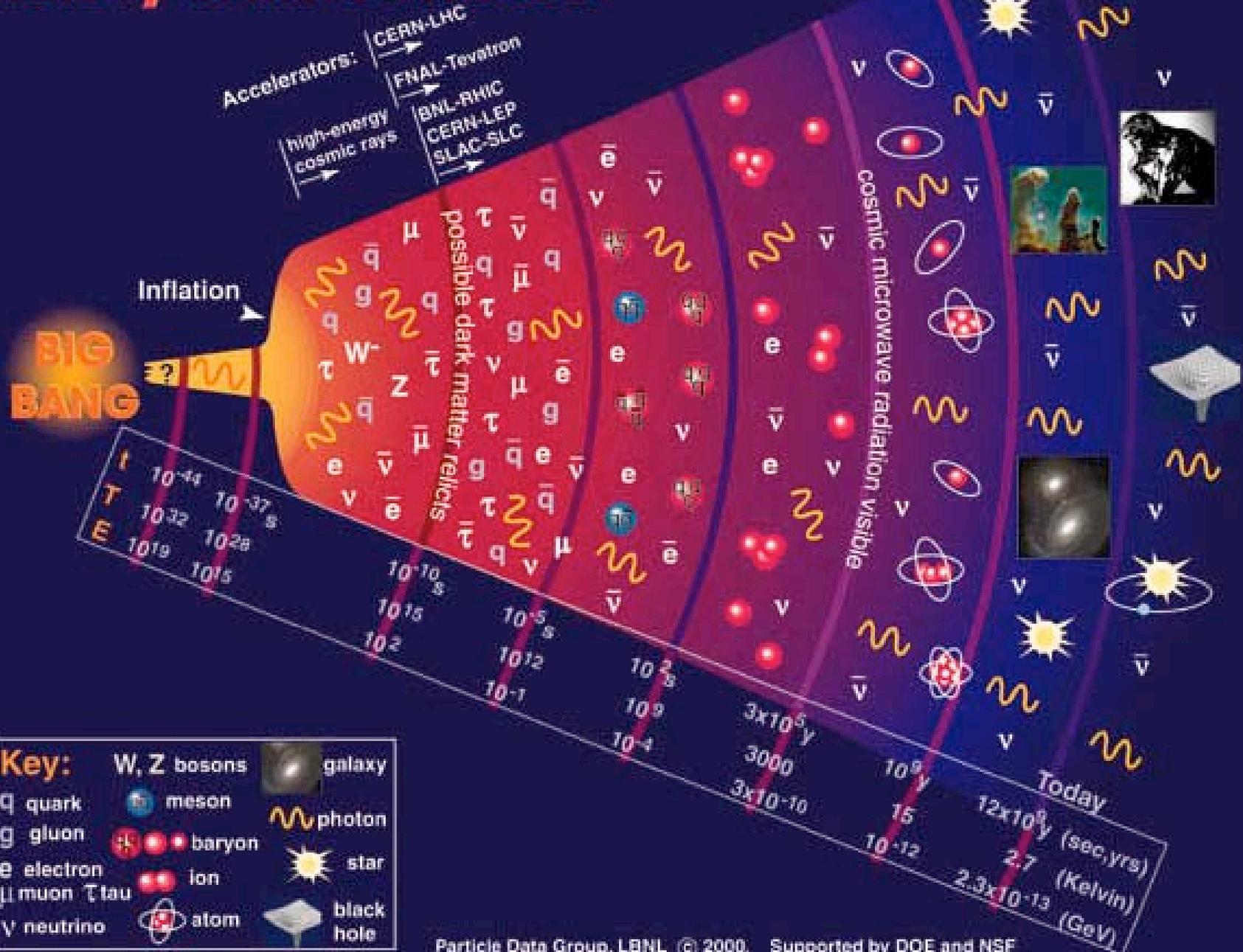
$$U_{MNSP} = \begin{pmatrix} \textit{big} & \textit{big} & \textit{small?} \\ \textit{big} & \textit{big} & \textit{big} \\ \textit{big} & \textit{big} & \textit{big} \end{pmatrix} \longleftrightarrow \text{?} \longleftrightarrow V_{CKM} = \begin{pmatrix} \textit{big} & \textit{small} & \textit{tiny} \\ \textit{small} & \textit{big} & \textit{tiny} \\ \textit{tiny} & \textit{tiny} & \textit{big} \end{pmatrix}$$

θ_{13}

- Leptogenesis and the role of neutrinos in the early Universe



History of the Universe



Matter-Antimatter Asymmetry ($\Delta B \neq 0$) from Leptogenesis

Cannot generate observed baryon asymmetry ($\Delta B \neq 0$) using quark matrix CP violation

Generate $\Delta L \neq 0$ in the early universe from CP (or CPT) violation in heavy neutrino N_3 vs. \bar{N}_3 decays (only needs to be at the 10^{-6} level)



B-L processes then convert neutrino excess to baryon excess.

Sign and magnitude ~correct to generate baryon asymmetry
in the universe with $m_N > 10^9$ GeV and $m_\nu < 0.2$ eV

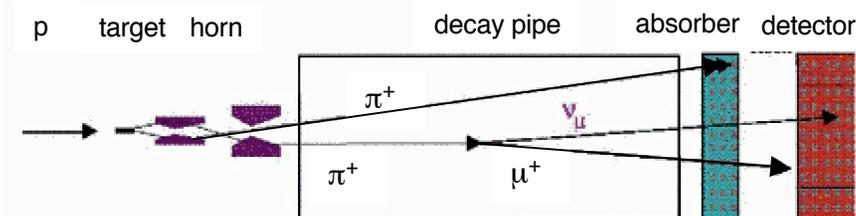
$$\text{Amount of CP violation is given by } J_{\text{lepton}} \sim \underbrace{\cos^2(\theta_{13})}_{\sim 1} \underbrace{\sin(2\theta_{12})}_{\sim 0.9} \underbrace{\sin(2\theta_{23})}_{\sim 1} \sin(2\theta_{13}) \sin(\delta_{\text{CP}})$$

Measuring θ_{13}

Method 1: Accelerator Experiments

$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \dots$$

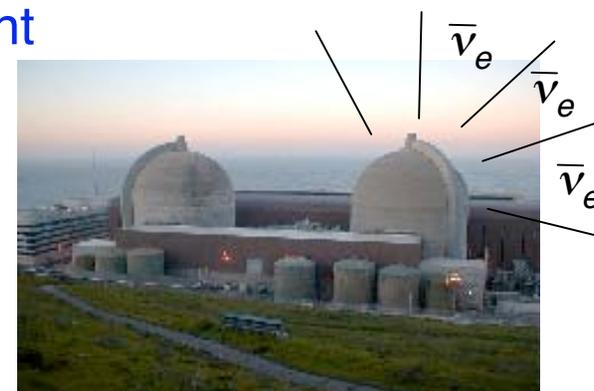
- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ yields θ_{13}, δ_{CP}
- baseline $O(100 - 1000 \text{ km})$, matter effects present



Method 2: Reactor Neutrino Oscillation Experiment

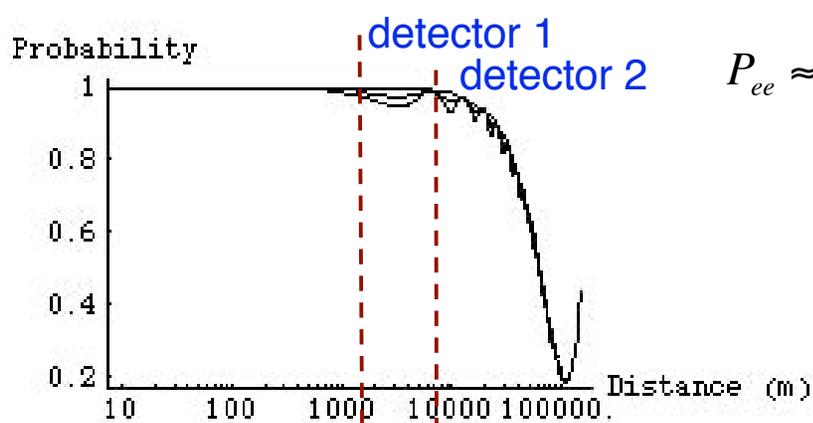
$$P_{ee} \approx 1 - \left(\sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{13} \right)$$

- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_x$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline $O(1 \text{ km})$, no matter effects



Measuring θ_{13} with Reactor Neutrinos

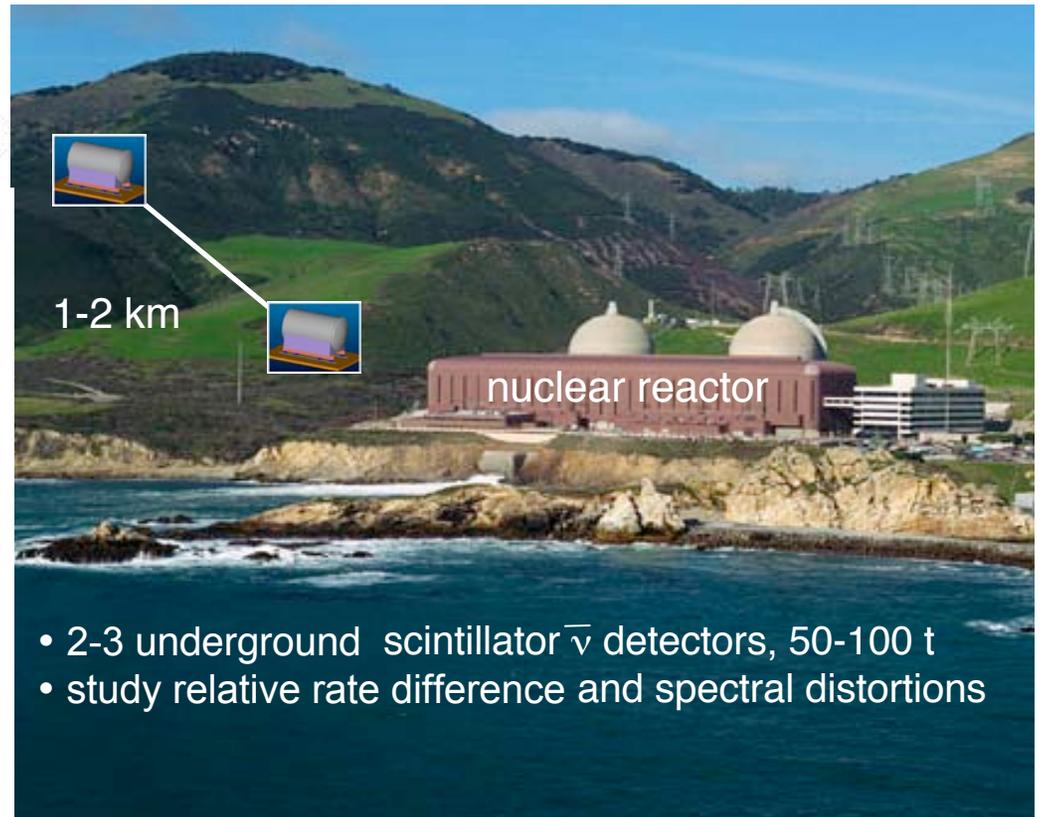
Novel Oscillation Experiment with Multiple Detectors



$$P_{ee} \approx 1 - \left(\sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{12} \right)$$

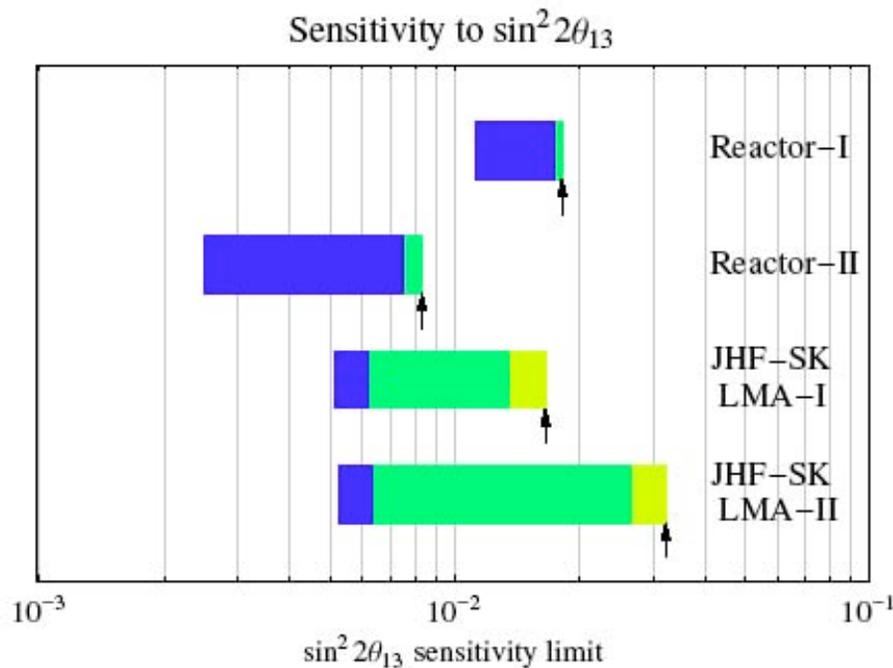
- relative ν flux measurement between 2 detectors
- eliminates most systematic errors
- projected sensitivity:
 $\sin^2 2\theta_{13} \approx 0.01-0.02$

Ref: theta13.lbl.gov, [hep-ex/0402041](https://arxiv.org/abs/hep-ex/0402041)

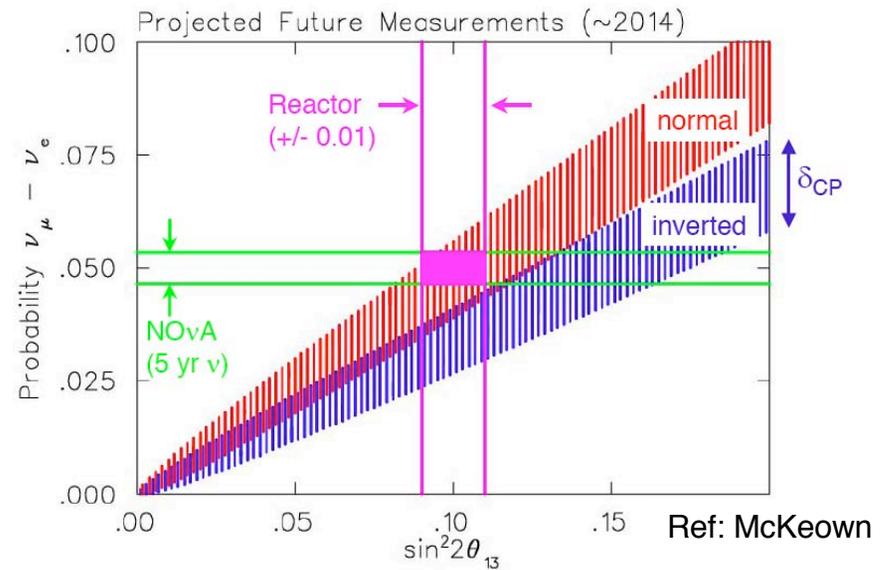


Determining the Three Unknowns in Oscillation Physics & The Role of a Reactor Neutrino Experiment

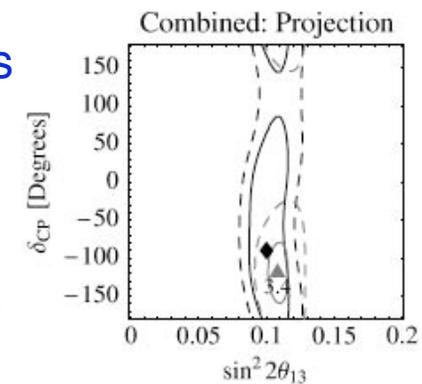
Precise Measurement of $\sin^2 2\theta_{13}$



Contribute to determination of sign of Δm^2 , i.e. mass hierarchy (in combination with accelerators)

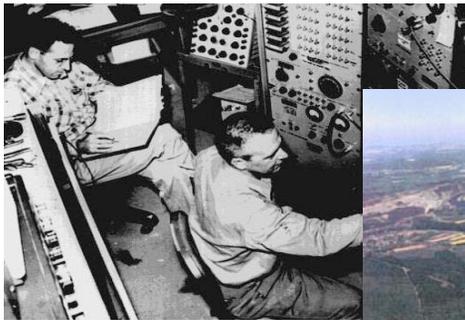


Constrain CP-violating parameters (in combination with accelerators)



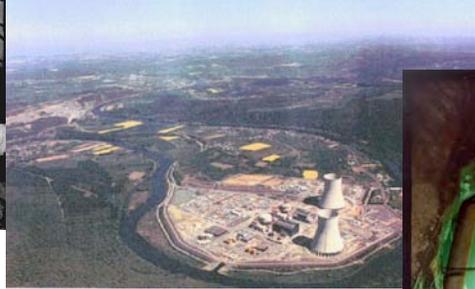
Outlook and Future Milestones

- Search for sterile ν , test of LSND by MiniBoone (2005?)
- Measurement of θ_{13} (2009?), towards the search for \not{CP} violation



1956

First observation
of neutrinos



1980s & 1990s
Reactor ν
measurements in
U.S. and Europe



2002

Evidence for $\bar{\nu}$ disappearance



2004 and beyond

Search for θ_{13}

- Other important ν questions remain: absolute mass, $0\nu\beta\beta$, \not{CP} , ...

